RF Energy Harvesting for INTERNET OF THINGS

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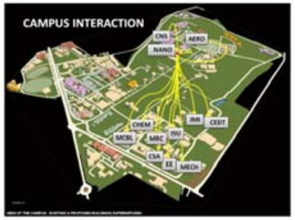
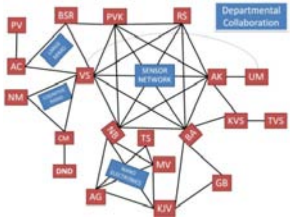
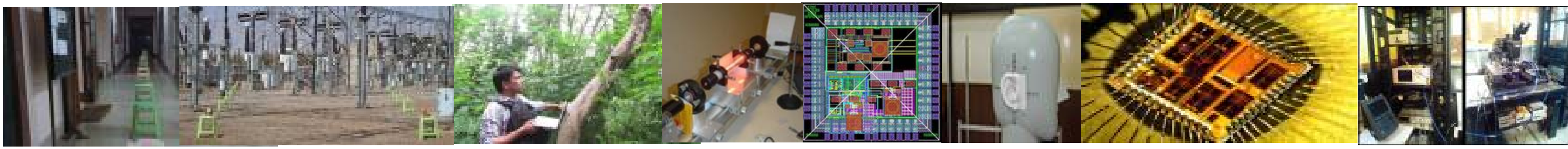
ECE Dept, Indian Institute of Science

- **Vision Statement:** Excellence in Theoretical and Experimental Research in Communications, Signal Processing, Microelectronics and RF/Photonics.
- **Faculty: 24;** Fellows of IEEE: 4; Fellows of INAE: 8
- Active in Publications: Books, Book Chapters, Journal & Conference Papers; Patents; Standardization etc
- Collaborative research

People
Masters Students
[ME, MSc→ Mtech, Mtech(Res)]
PhD Students
Project Staff





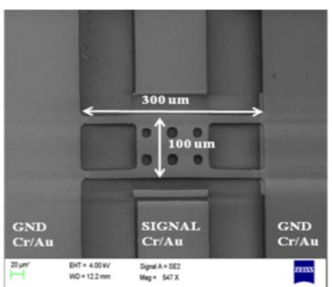


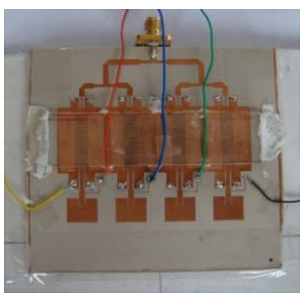
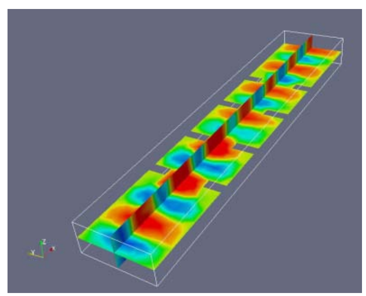
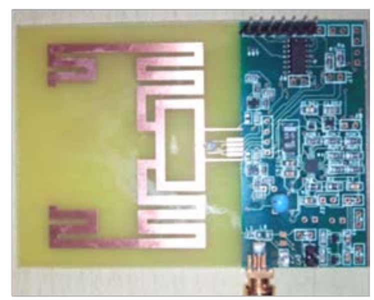
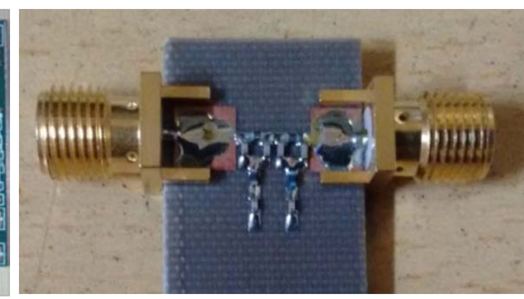
ECE: Microwave Engineering

K.J. Vinoy

- Low-Actuation Voltage Capacitive RF MEMS Switch (<10V)
  - Low-complexity fabrication process to enhance process yield
  - High reliability: no failure even up to 10 million cycles of operation tested
- Meso-scale Electrostatic Phase Shifter on microwave Laminate (MEPL)
  - Utilizes modern printed circuit board fabrication technology.
  - X-band monolithic antenna array system on the microwave laminate board demonstrated.

- Wideband group delay engineering in RF circuits for radar, medical imaging, and spectrum sensing.
  - Demonstration uses two stage All – Pass Networks; can be extended over multiple stages to obtain a higher bandwidth and/or higher group delay slope.
- RF energy harvesting circuits
  - Integrated with RF transmitters and sensors for practical IoT nodes
  - High efficiency RF-DC converter which can operate at input power of -20dBm (10µW) at 2.4GHz using UMC 130nm process MOSFETs.
- FEM based algorithms for Electromagnetic circuits & components (periodic structures such as metamaterials)
  - Fast computation of electromagnetic propagation characteristics
  - Especially suited for evaluation of processes uncertainties



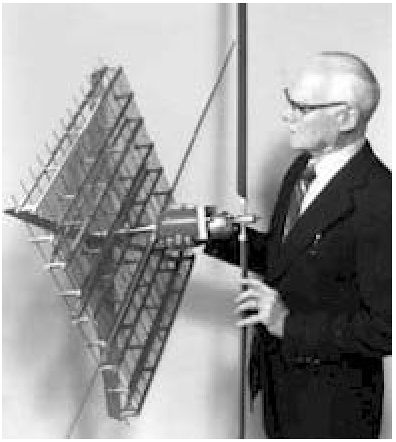





Setting the stage….

- **Introduction**
  - **Wireless Power Transfer**
    - **Energy Harvesting**
  - **Internet of Things**
- Highlights of Recent Development (Hardware)
  - Powering wireless terminals
  - RFID with integrated sensors

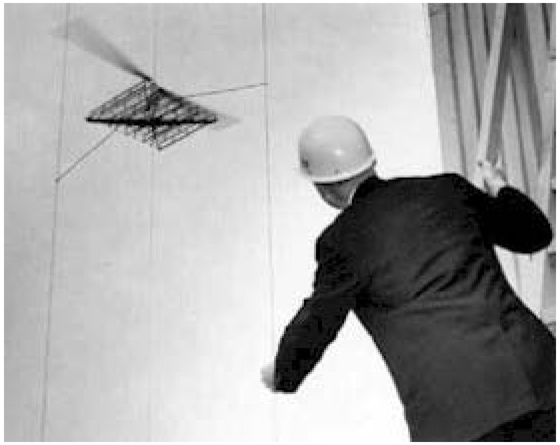
Ongoing Research Challenges

Wireless Power Transfer (WPT)



- Indicates transfer of electric energy remotely

- WPT has a long history!!
  - Tesla demonstrated it in 1899 by wirelessly powering fluorescent lamps 40 kms away from the power source.
  - Had multiple patents in early 1900s.



- In 1960s W.C. Brown coined the term Rectenna, which he used to directly converts incoming microwaves to DC.
  - He demonstrated its ability to power a helicopter solely through microwaves for 10 hours continuously.

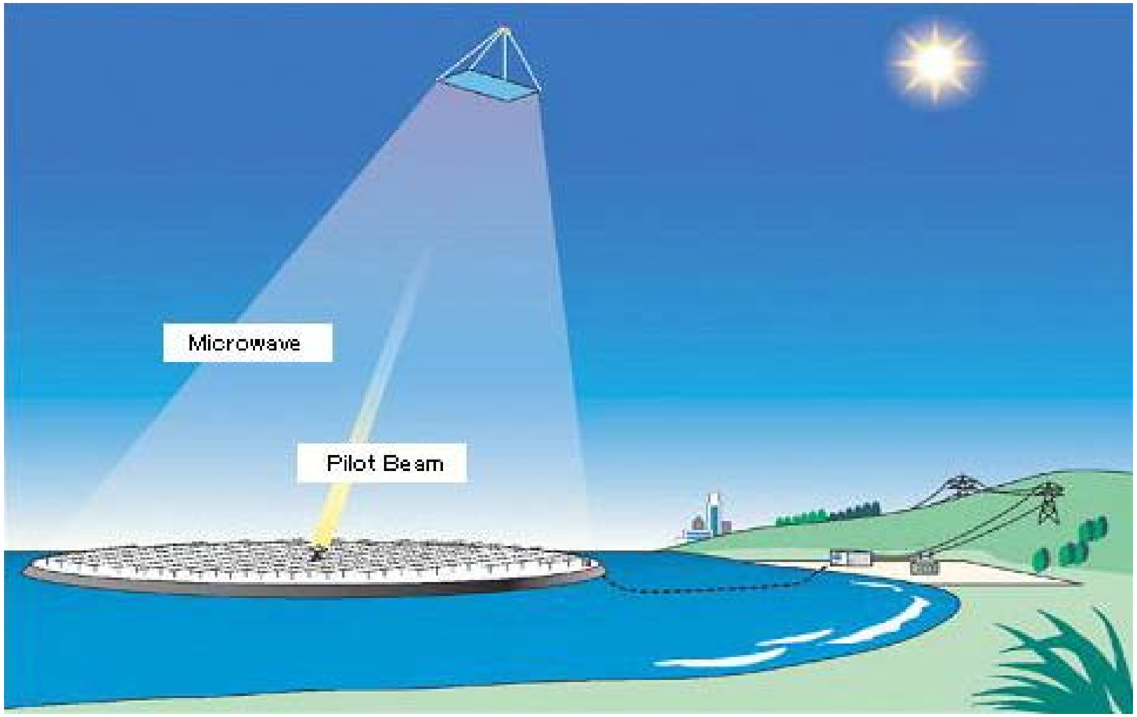
- These demonstrations involved dedicated sources with **large power to transmit over long distances**.

http://mainland.cctt.org/istf2008/brown.asp

SSPS

- Space Solar Power Satellites

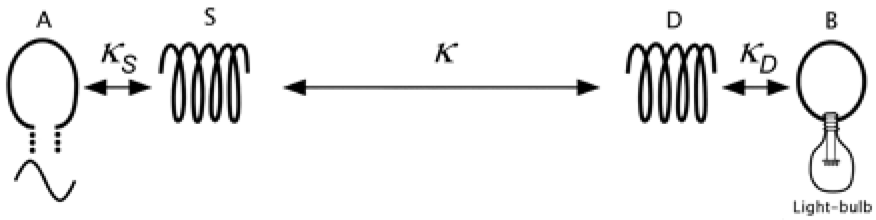
- WPT is widely investigated for putting **solar power generating satellites** into space and transmitting power to Earth stations. (Mainly in Japan)

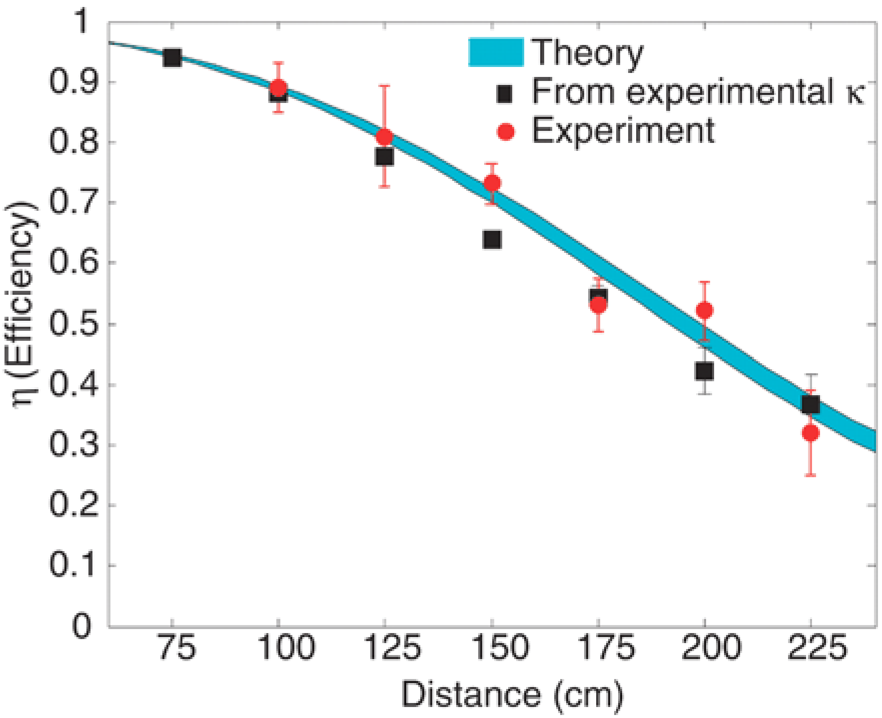


http://www.jspacesystems.or.jp/en_project_ssps/

Near field Wireless Power Transfer

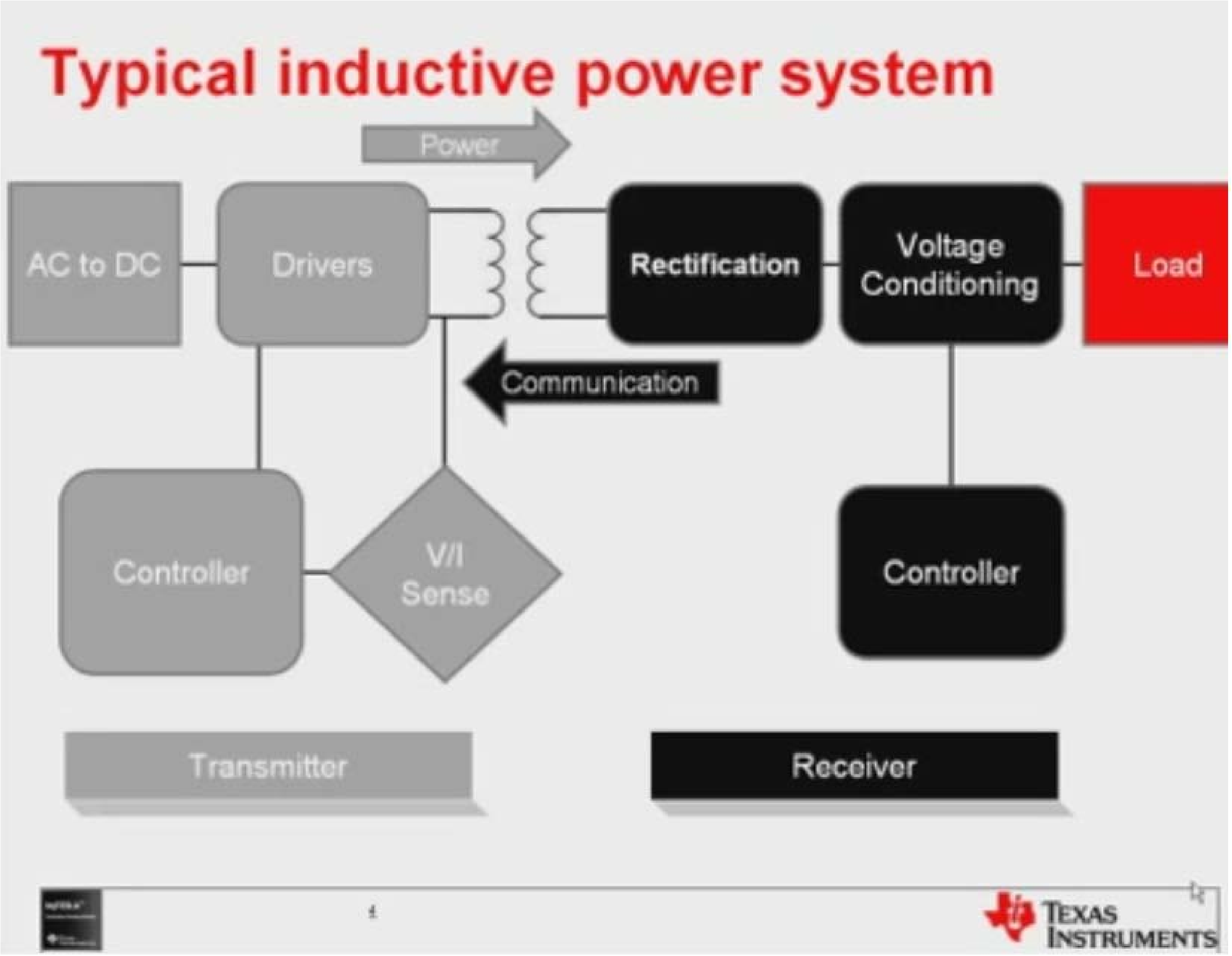
- Recent demonstration by MIT to transfer high RF power (Watts) transferred across meters.
- Resonant coils are used
- Typically at 100 kHz to 10’s of MHz
- Many new applications emerged





André Kurs et al, Wireless Power Transfer via Strongly Coupled Magnetic Resonances , Science, Vol. 317 no. 5834 pp. 83-86. 6 July 2007.

System Schematic Qi

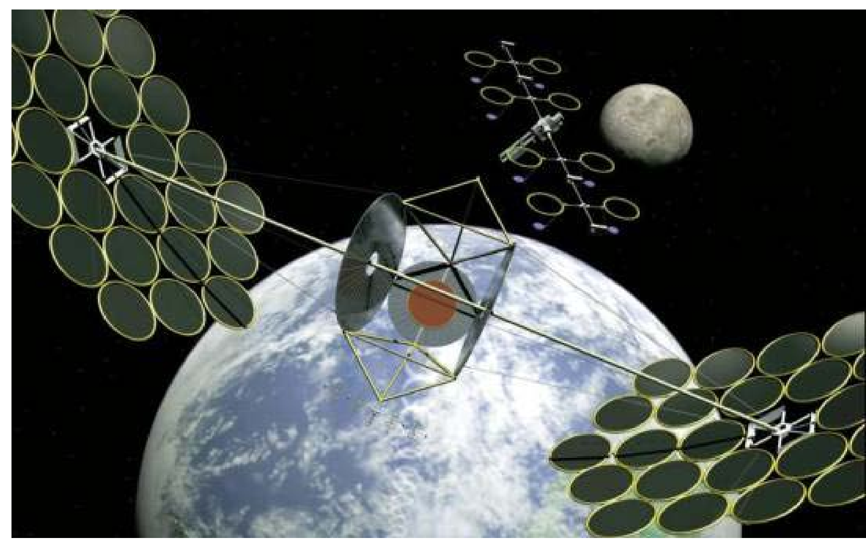


Source: Texas Instruments Qi Development kit

Far → Near in WPT

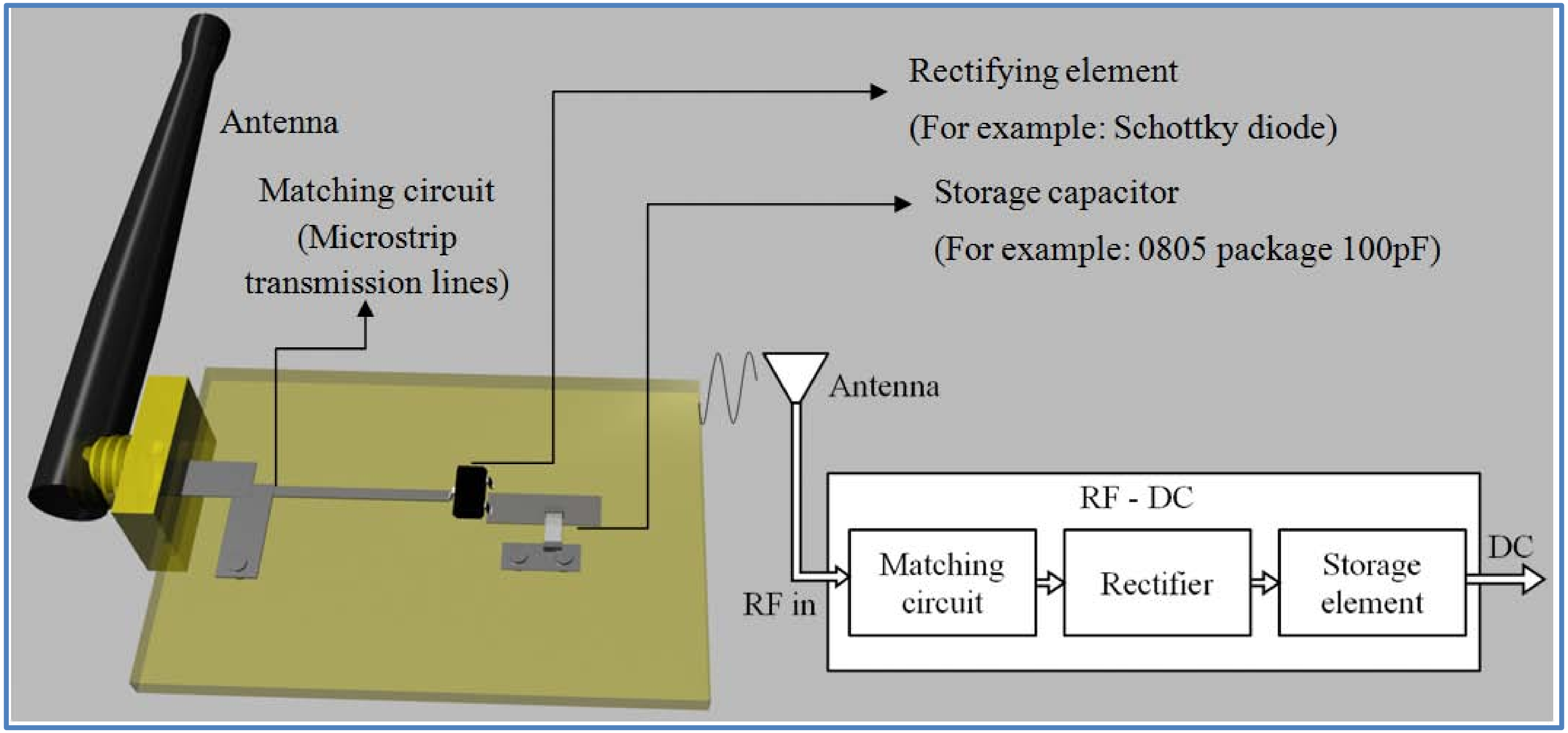
- Free space loss factor is a major bottleneck for power transfer at large distances

- Short distance/ Near field options
  - MIT demonstration (2007)
  - Qi Standard
  - Phone charging solutions
  - Vehicles running on wireless power
- Two extremes in WPT
  - mW ← → MW
  - mm ← → 1000s km
  - 100kHz ← → 2.4/5.8GHz
  - 10cm x 10cm ← → km x km
  - Commercial vs bluesky



Far Field Transfer of RF Energy

- Focus of this talk
- Applications: RFID tags, Wireless Sensor Network nodes, biomedical equipment, home automation and structural monitoring can benefit from RF energy harvesting.
- Block diagram and a design example:



A New Paradigm: Internet of Things (IoT)

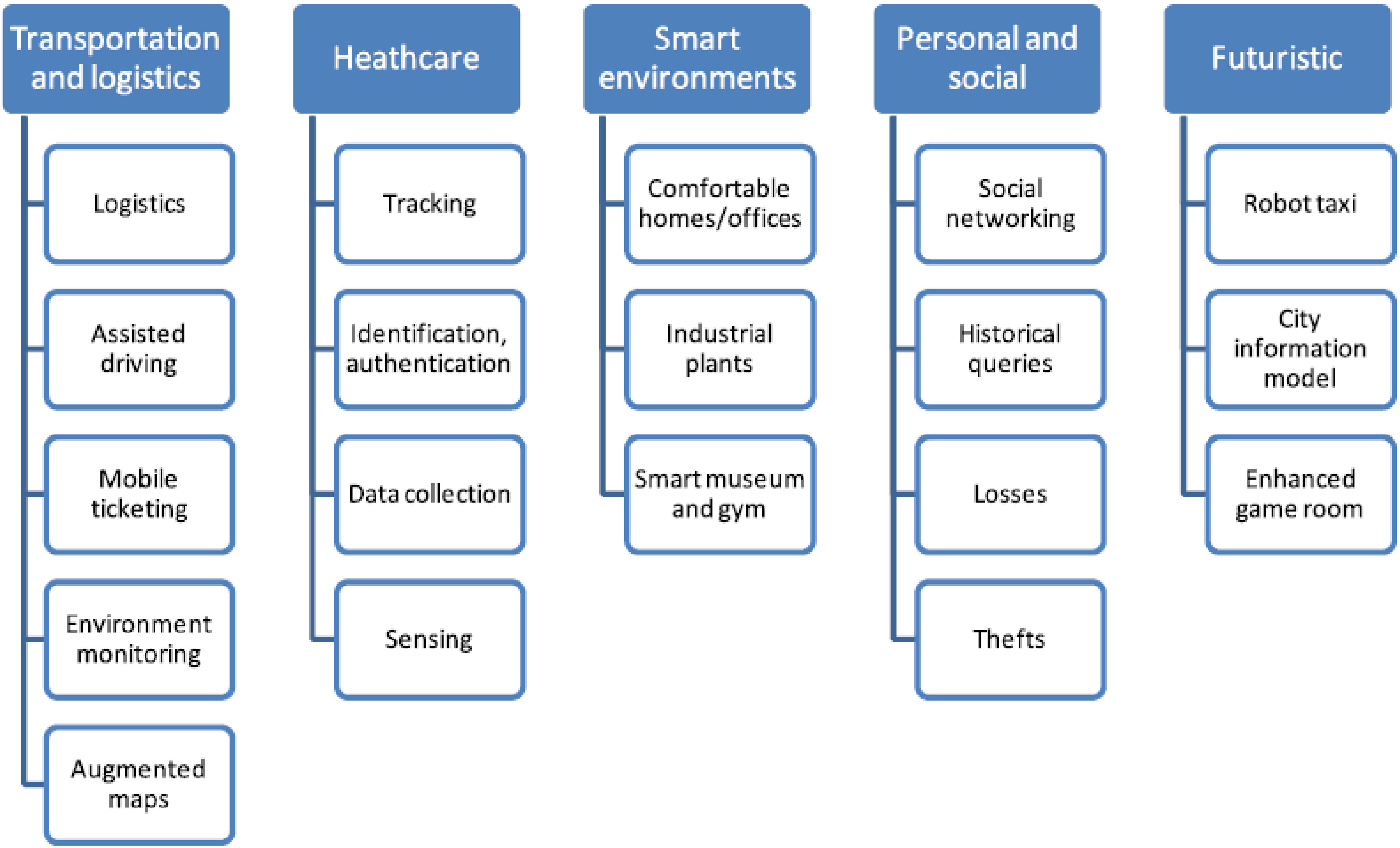
- IoT refers to uniquely identifiable objects and their virtual representations in an Internet-like structure.

Connects Anytime, Anyplace for Anyone (ICT)
AAA + for Anything (IoT)

- IoT is a scheme for connecting things: sensors, actuators, and other smart technologies, thus enabling person-to-object and object-to-object communications.

- **Continuous availability of power is crucial for their deployment**

IoT Applications



L. Atzori , A. Iera, G. Morabito, The Internet of Things: A survey Computer Networks 54 (2010) 2787–2805

Comparison of different wireless protocols

Today, a lot can be done at low power!!

Characteristics of key 2.4GHz ISM Band Radios studied :

	BLE	ANT	Zigbee	WLAN
Topologies	P2P , Star	P2P , Star, tree, mesh	P2P , Star, mesh	P2P , Star
Modulation	GFSK	GFSK	OQPSK	DSSS (802.11b)
Max data rate	1Mbps	12.8-60 Kbps	250Kbs (@2.4Ghz)	1- 11Mbps (802.11b)
Throughput	305 kbps	20Kbps	100Kbps	6Mbps (802.11b)
Range (in m)	10-100(0-10dBm)	30 (@ 0dBm)	10-100 (0-20dBm)	100+(20dBm)
Max nodes in piconet	7	65533	Star-65536	32-64
Battery life	1-2 years (coin cell)	1-2years (coin cell)	100-1000 days	0.5-5days

Key Aspects :

BLE is robust and has lowest power consumption but cannot natively form mesh networks,

Zigbee can support large mesh networks, power consumption is higher than BLE and throughput is lower: It is suitable for low data rate, low power, large size networks.

WLAN is primarily suitable for transferring bulk data at high speeds, Not suitable for low power applications.

Power Requirements in Common WSN

	Crossbow MICAz	Intel IMote2	Jennic JN5139
Radio standard	IEEE802.15.4/ZigBee	IEEE802.15.4	IEEE802.15.4/ZigBee
Typical range	100m (outdoor), 30m (indoor)	30m	1 km
Data rate (kbps)	250 kbps	250 kbps	250 kbps
Sleep mode (deep sleep)	15 μA	390 μA	2.8 μA (1.6μA)
Processor only	8mA active mode	31–53mA∗	2.7+0.325mA/MHz
RX	19.7mA	44mA	34mA
TX	17.4mA (+0dbm)	44mA	34mA (+3 dBm)
Supply voltage (minimum)	2.7V	3.2V	2.7V
Average	2.8mW	12mW	3mW

JM. Gilbert∗ F. Balouchi, Comparison of Energy Harvesting Systems for Wireless Sensor Networks, International Journal of Automation and Computing 05(4), October 2008, 334-347

	Jennic JN5148	TI- CC430	BLE	Zarlink ZL70250
Active mode current at 16MHz [mA]	6	4	6.7	3.2
Deep sleep current [nA]	100	1000	400	20
Transmission current [mA]@Tx-power [dBm]	15@2.5	18@0	36@2	2@-10
Transmit frequency	2.4 GHz	2.4 GHz	2.4 GHz	868 MHz
Wakeup time [ms]	1	3	0.12	0.16
Energy consumption for a transmission cycle of 2ms [µJ]	183	300	196	32
Power supply voltage [V]	2.2 – 3.6	1.8 -3.6	2-3.6	1.2 – 1.8

In perspective

- Energy requirements in different devices/systems
- 6 orders of magnitude variation!!!
- Energy requirements in WSN
  - Depends on the complexity/ standard/ range
  - eg 90 μW to power a pulse oxymeter sensor, to process data and to transmit them at intervals of 15 s

Device type	Power consumption
Smartphone	1W
MP3 decoder chip	58 mW
Hearing aid	1 mW
Wireless sensor node	100 μW*
RF receiver chip	24 mW
GPS receiver chip	15 mW
6D motion sensor	14.4 mW
Cell phone (standby)	8.1 mW
PPG sensor	1.473 mW
Humidity	1 mW
Pressure	0.5 mW
3D accelerometer	0.324 mW
Temperature	27 μW
Cardiac pacemaker	50 μW
Wristwatch	7 μW
Memory R/W	2.17 μW
A-D conversion	1 μW

J Yun, S. Patel, M.Reynolds, G. Abowd "A Quantitative Investigation of Inertial Power Harvesting for Human-powered Devices," UbiComp'08, September 21-24, 2008, Seoul, Korea.

R.J.M. Vullers, et.al, Micropower energy harvesting, Solid-State Electronics 53 (2009) 684–693

Power Density from Various Harvesters

Ambient RF	< 1 μW/cm^2
Ambient light	100 mW/cm^2 (directed toward bright sun)
	100 μW/cm^2 (illuminated office)
Thermoelectric	60 μW/cm^2
Vibrational	4 μW/cm^3 (human motion ~Hz)
microgenerators	800 μW/cm^3 (machines ~kHz)
Ambient airflow	1 mW/cm^2
Push buttons	50 μJ/N
Hand generators	30 W/kg
Heel strike	Up tp 7 W for 1 cm deflection

Power requirements in conventional sensor network nodes may not be met by harvesting alone!

J Yun, S. Patel, M.Reynolds, G. Abowd "A Quantitative Investigation of Inertial Power Harvesting for Human-powered Devices," UbiComp'08, September 21-24, 2008, Seoul, Korea.

Electromagnetic: Solar → RF

- PV is a good source of energy. Recall,

Ambient light	100 mW/cm^2 (directed toward bright sun)
	100 $\mu W/cm^2$ (illuminated office)

- However, it light is not always available.
  - At night
  - Specific scenarios: in a closed chamber, or mine.

- RF is an alternative
  - Unlike others, RF sources may be ambient or intentional.
  - Ambient sources such as base stations or broadcast stations
  - Special sources: RF ID reader, Phone charger, special beacons

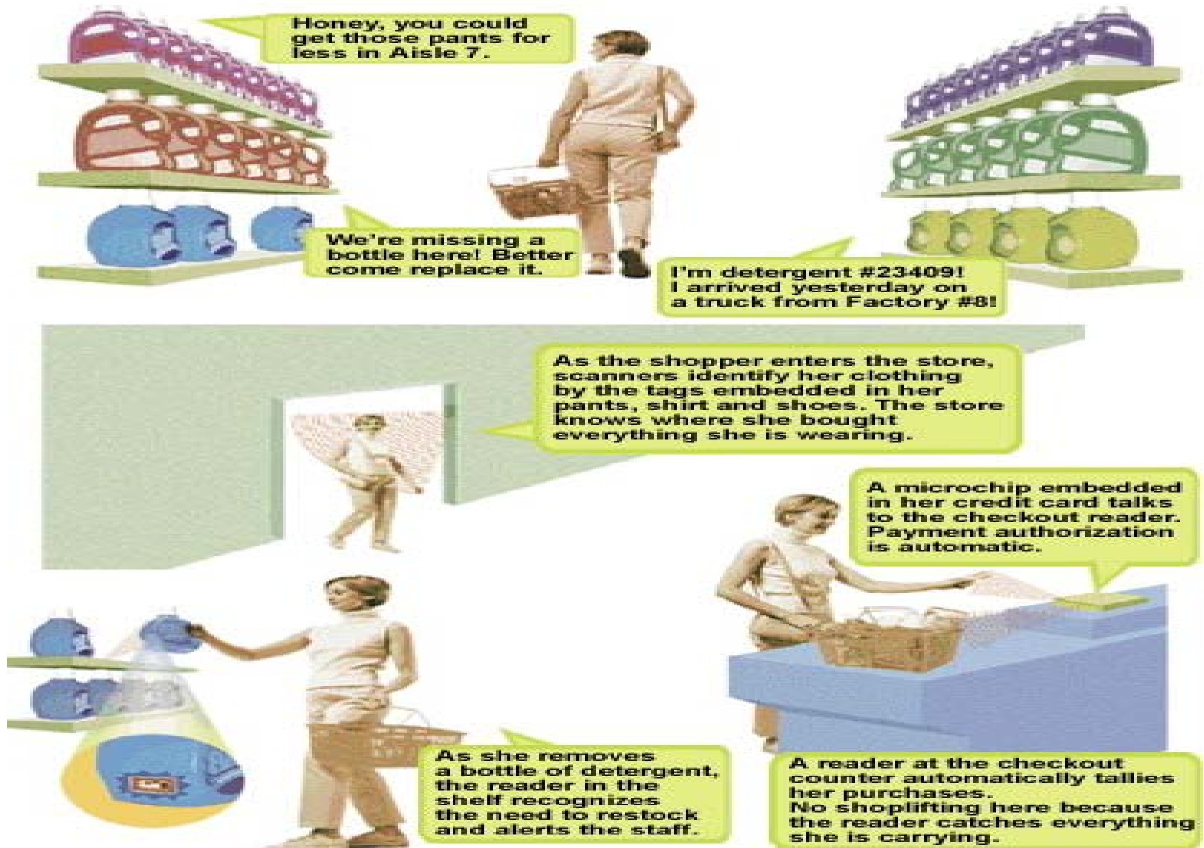
Demand and Supply

- The peak currents needed during transmit and receive operation is not achievable using the harvester alone.
- Buffering is also needed to ensure continuous operation during times without power generation.
- The combination of an energy harvester with a small-sized storage is the best approach to enable energy autonomy of the network over the entire lifetime.
  - Rechargeable battery
  - Thin film batteries
    - can be integrated directly in Integrated Circuit (IC) packages in any shape or size,
    - Flexible when fabricated on thin plastics
    - Thin film batteries have high impedance;
    - Low discharge efficiency compared to Li-ion batteries
  - super capacitor
    - Leakage in super capcitors depends on the voltage. Low at low voltage

Internet of Things (IoT)

Embedding short-range mobile transceivers into a wide array of gadgets and everyday items, enabling new forms of communication between people and things, and between things themselves.

RFID + Sensor + Smart Tech + Nano Tech = IoT



When shopping in the market, the goods will introduce themselves.

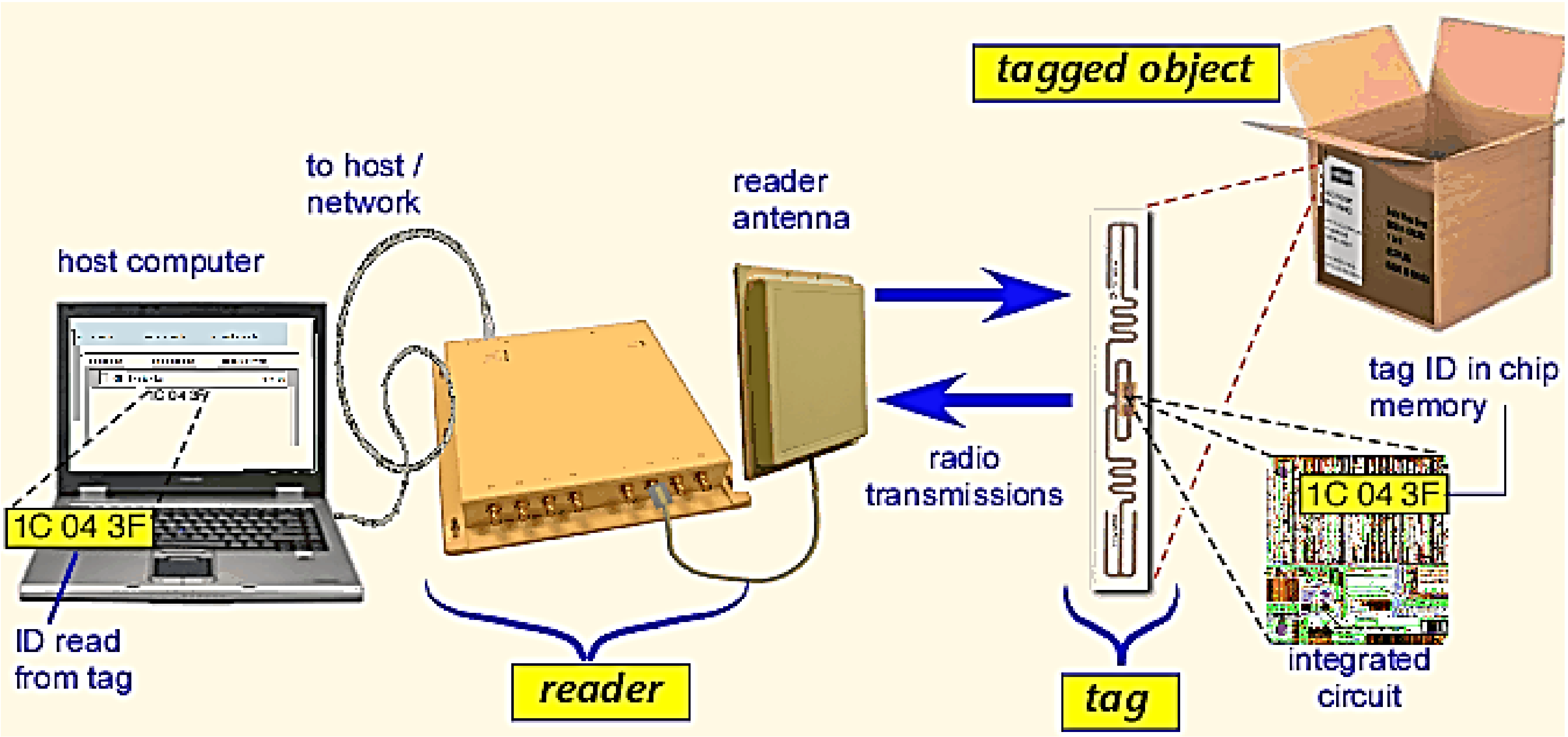
When entering the doors, scanners will identify the tags on clothing.

When paying for the goods, the microchip of the credit card will communicate with checkout reader.

When moving the goods, the reader will tell the staff to put a new one.

Introduction to RFID

- The reader converts incident field and returns useful data
- In passive RFID systems reader transmits EM energy that "wakes up“ the tag and provides power for the tag to respond to the reader.



Backscatter Communication

- **Backscatter** is the reflection of signals back towards their source.
  - In this scheme, two devices communicate using incident (or ambient) RF as the source of power.
  - Backscattering is achieved by changing the impedance of a receiver in the presence of an incident signal.
  - When waves encounter a new media that have different impedances, a part of the wave is reflected.
  - The reflection depends on the difference in the impedances.
- By modulating the impedance at the receiver port, one can control the scattered RF energy, hence enabling information transmission.

abc.cs.washington.edu/files/comm153-liu.pdf

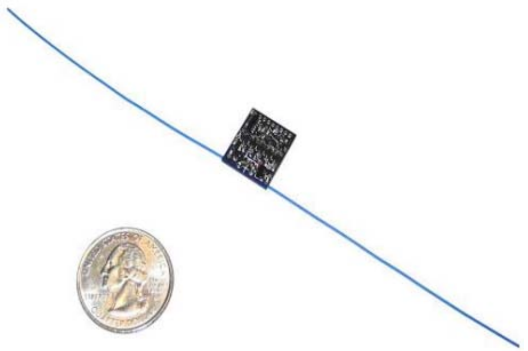
RFID → IoT

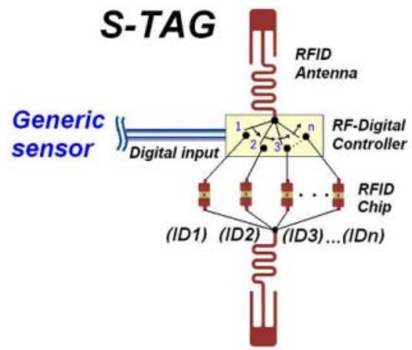
- RFID
  - Uses radio waves for identifying or tracking the object.
  - Proven to be a simple and cost effective system
  - Tags are very cheap and is possible to be attached to everyday objects.

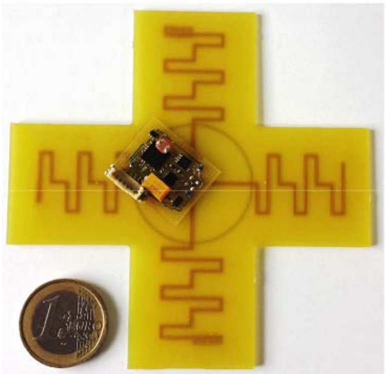
- RFID is considered a prerequisite of **Internet of Things.**

- **Example: RFID tags can be integrated with sensors**
  - When a reader reads a tag, the sensor information will be sent to the reader along with the identity of the object.

Some Examples



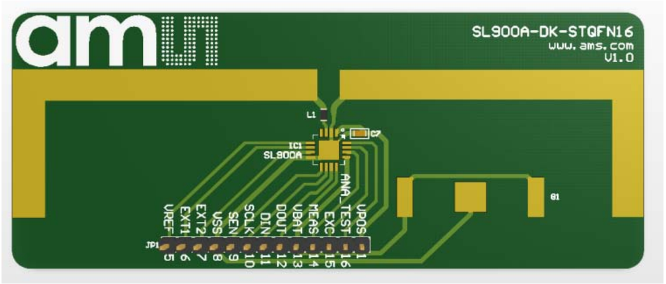


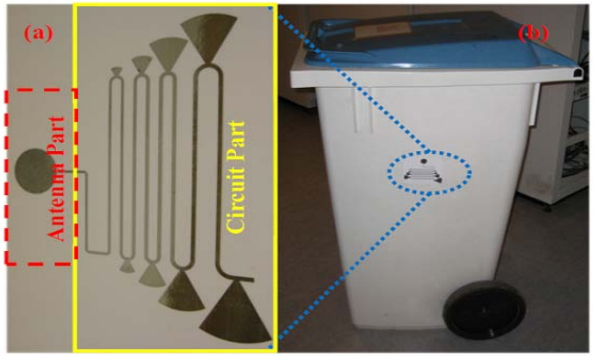


Discrete Element Based
WISP (Wireless Identification Sensing Platform)

Multi-Chip Based S-tag

Chips with I2C / SPI
SPARTACUS / RAMSES (Self-Powered Augmented RFID Tag for Autonomous Computing and Ubiquitous Sensing / RFID Augmented Module for Smart Environmental Sensing)





Single IC Based Sensing Tags

Printed Chipless RFID Tag

WISP

- Wireless Identification Sensor Platform (2009)
  - WISPs are a wireless, battery-free sensing and computation platform, powered by harvested energy from off-the-shelf UHF RFID readers.
  - To a RFID reader, a WISP is a EPC gen1 or gen2 tag; but inside the WISP, the harvested energy is operating a 16-bit general purpose microcontroller.
  - The microcontroller can perform computing tasks, including sampling sensors, and communicate to the RFID reader.
  - WISPs have been built with various sensors, WISPs can write to flash and perform cryptographic computations.

A collaboration between Intel Research Seattle and the University of Washington.

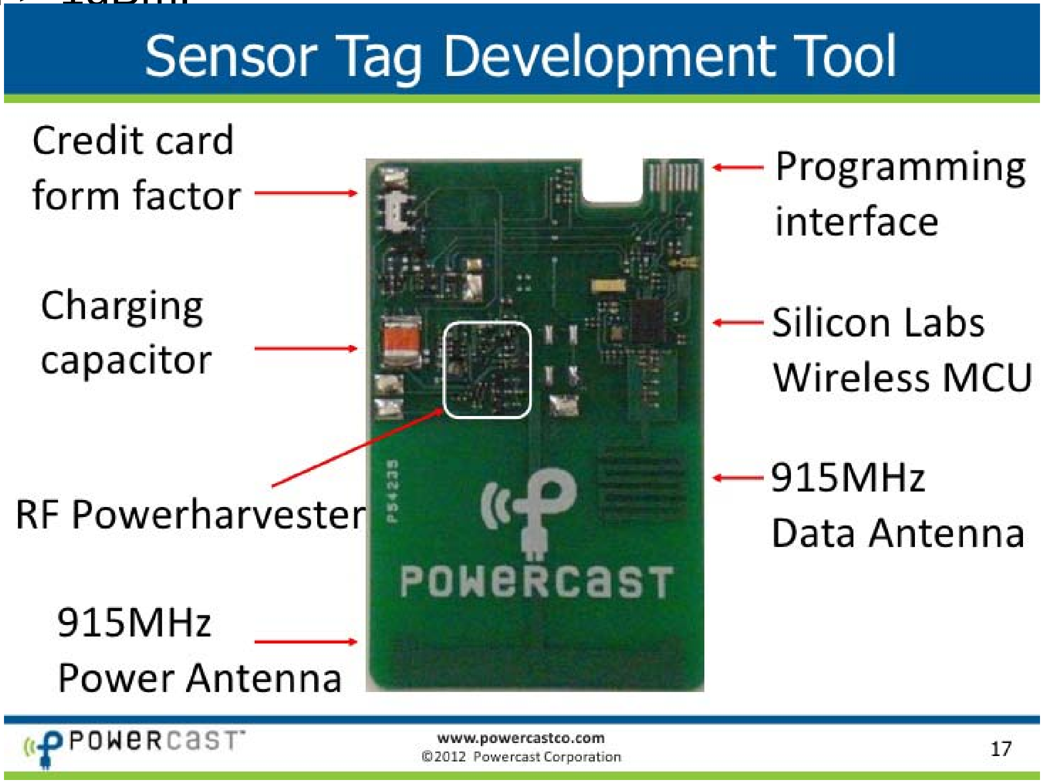
http://wisp.wikispaces.com/Wisp+4.1+DL

RFID Sensors (Products)

- ID operation is passive; yet most sensors require power sources

- Powercast has a wireless sensor that is battery-less. Uses RF energy harvesting.
- Harvesting schemes works at power as low as -12dBm. (RF-DC conversion efficiency above 40% only above -8dBm)
- Harvested power >0.4mW for RF in of >-1dBm.
- Multiple custom ICs and discretes

- Other suppliers include
  - Phase IV
  - RFID sensor systems
  - etc



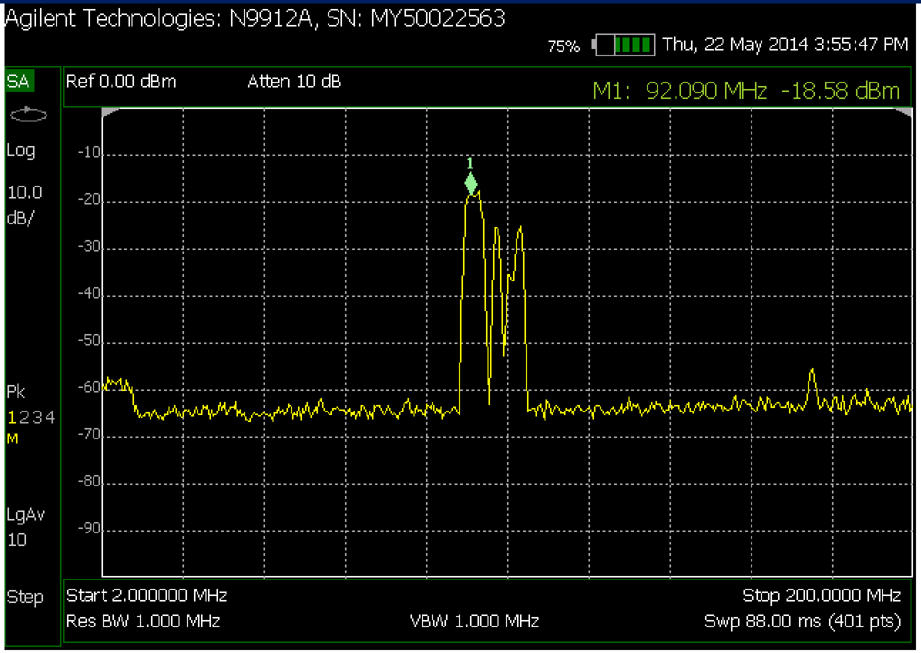
http://www.powercastco.com/uhf-rfid-sensing-passive-rfid-wireless-sensor-tags/

Battery-less Wireless Terminals

- Most of our work in this direction was towards battery-less terminals
- Long life terminals without wiring
- These are useful when
  - Terminals are embedded within structures (or body)
  - Devices to be deployed in hostile environments
  - Use of battery is not allowed (potential cause for explosion)
- Other factors
  - Cost, weight, etc.
- Primary focus: use of radio frequencies (ambient/intentional)

Ambient RF Sources

- Several sources:
  - WiFi Access points (mW) [2.4/.6GHz]
  - Cellular Tower (W) [900/1800 MHz]
  - TV Broadcast (MW) [150-450MHz]
  - FM broadcast (kW) [90-108MHz]
  - AM Radio broadcast (kW) [<1MHz]

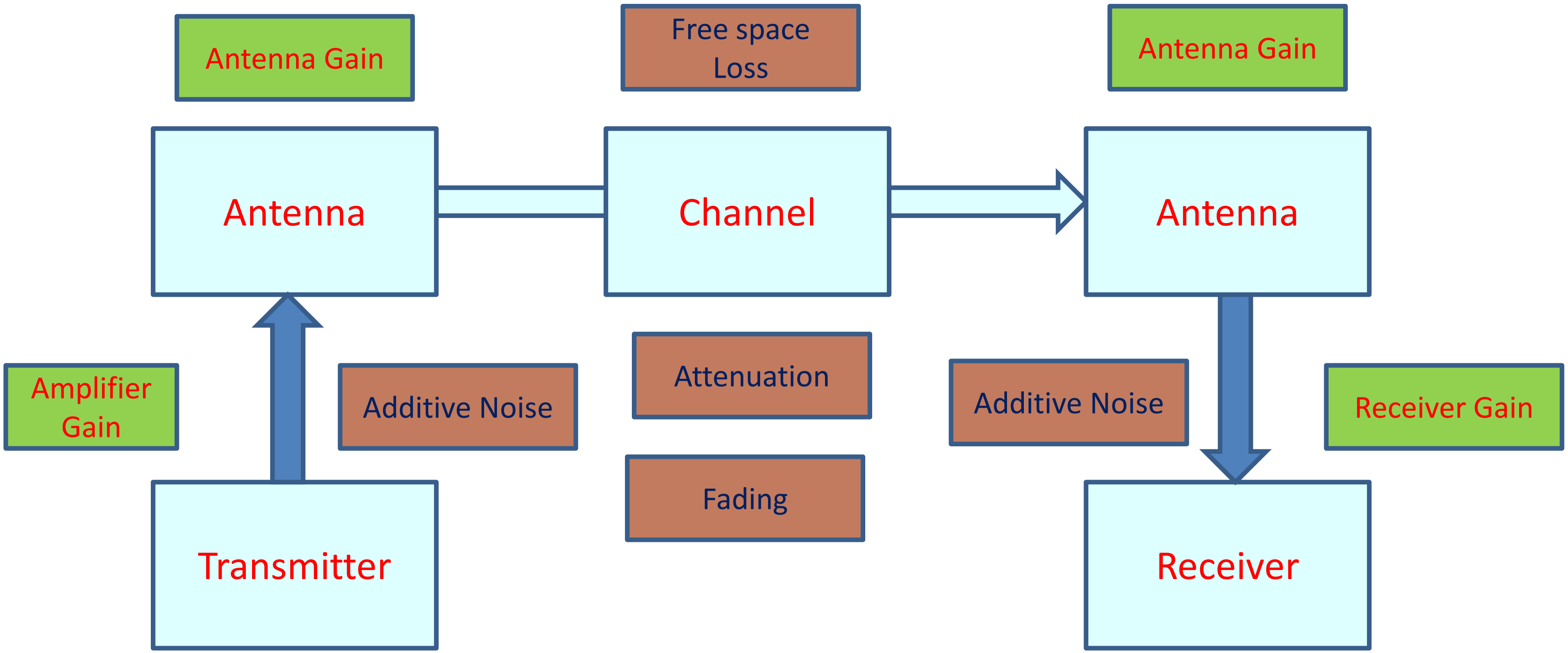


- In general
  - Lower frequencies help non-line-of sight propagation
  - Power availability from ambient sources is limited and varies from place to place.

- Note
  - Unlike other sources, most practical RF harvesters (eg in RF ID) depend on **intentionally generated energy**.
  - This is called **wireless power transfer (WPT)** in the conventional RF/Microwave parlance.

Wireless Communication System

- Power transfer scheme is no different!!



Antenna Fundamentals: Directivity

This is the ratio of the radiation intensity in a given direction to the radiation intensity averaged over all direction

Average radiation intensity, $U_0 = \dfrac{P_{rad}}{4\pi}$

Directivity,

$$D(\theta,\phi) = \frac{U(\theta,\phi)}{U_0} = \frac{4\pi U(\theta,\phi)}{P_{rad}}$$

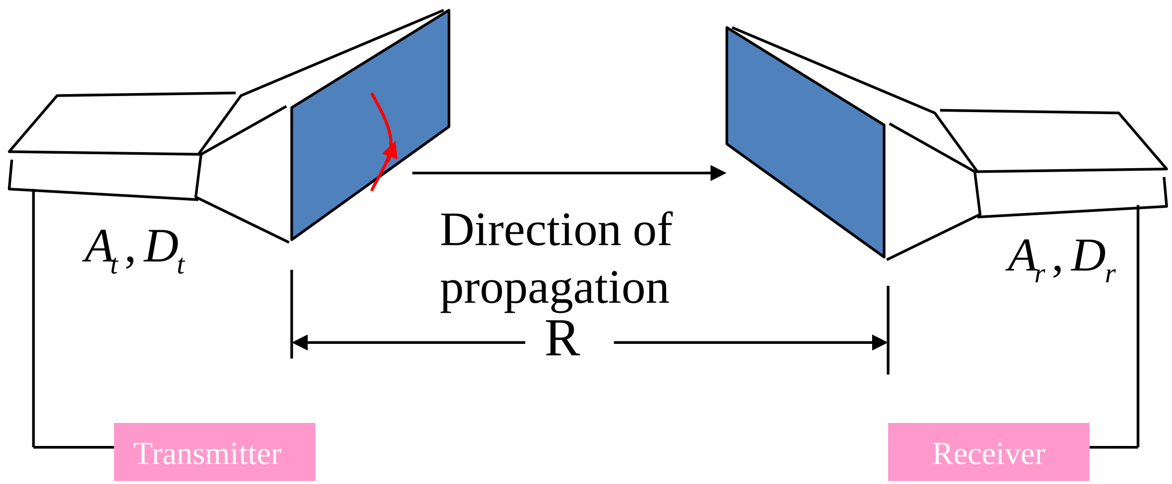
- If direction is not specified, it implies the direction of maximum radiation intensity

$$D_{\max} = \frac{4\pi U_{\max}}{P_{rad}} \qquad D_{dB} = 10\log D$$

Maximum directivity and Maximum effective area

The radiated power density by a transmitter at a distance R

$$W_t = \frac{P_t D_t}{4\pi R^2}$$



Power received

$$P_r = W_t . A_r = \frac{P_t D_t A_r}{4\pi R^2}$$

$$or,\ D_t . A_r = \frac{P_r}{P_t} . 4\pi R^2$$

$$\therefore \frac{D_t}{A_t} = \frac{D_r}{A_r}$$

$if,\ D_0 = \text{max. directivity}$

$A_{em} = \text{max. effective area}$

By reversing the transmission direction

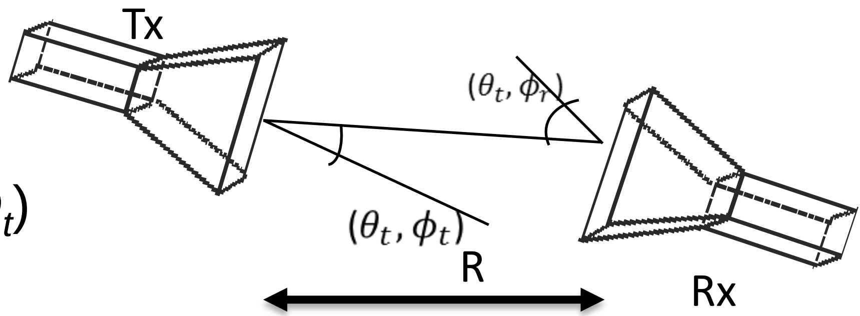
$$D_r A_t = \frac{P_r}{P_t} \cdot 4\pi R^2$$

this can be generalized by

$$\frac{D_1}{A_1} = \frac{D_2}{A_2} = k = \frac{4\pi}{\lambda^2}$$

$$D = \frac{4\pi A_{em}}{\lambda^2}$$

Frii’s Transmission Equation



- The radiation intensity for an isotropic radiator is $W_0 = \frac{P_t}{4\pi R^2}$
- For an antenna of gain G_t (or directivity D_t)

$$W_t = \frac{P_t G_t(\theta_t,\phi_t)}{4\pi R^2} = e_t \frac{P_t D_t(\theta_t,\phi_t)}{4\pi R^2}$$

- The effective aperture of a receiving antenna is given by $A_r = e_r D_r(\theta_r, \phi_r)\frac{\lambda^2}{4\pi}$
- Therefore,

$$P_r = e_r D_r(\theta_r, \phi_r)\frac{\lambda^2}{4\pi} W_t = e_t\, e_r D_t(\theta_t, \phi_t) D_r(\theta_r, \phi_r)\frac{\lambda^2}{(4\pi R)^2}\,|\hat{\boldsymbol{\rho}}_t \cdot \hat{\boldsymbol{\rho}}_r|^2$$

$$\frac{P_r}{P_t} = e_t e_r D_t(\theta_t, \phi_t) D_r(\theta_r, \phi_r)\frac{\lambda^2}{(4\pi R)^2}\,|\hat{\boldsymbol{\rho}}_t \cdot \hat{\boldsymbol{\rho}}_r|^2$$

$$\frac{P_r}{P_t} = e_{cdt} e_{cdr}(1-|\Gamma_t|^2)(1-|\Gamma_r|^2) D_t(\theta_t, \phi_t) D_r(\theta_r, \phi_r)\frac{\lambda^2}{(4\pi R)^2}\,|\hat{\boldsymbol{\rho}}_t \cdot \hat{\boldsymbol{\rho}}_r|^2$$

- When the antennas are pointing towards each others’ peak radiation direction,

$$\frac{P_r}{P_t} = G_{0t} G_{0r}\left(\frac{\lambda}{4\pi R}\right)^2$$

Note that includes a loss factor (usually called **Free space Loss factor)**
Does not include dissipation/attenuation in medium; caused by spreading

Some numbers on Radiative form of WPT…

- Practical systems will have
  - Operational frequencies in ISM bands.
  - Most terminals are compact.
  - Antenna efficiency is compromised.
  - Nearly isotropic radiations expected.

- Main bottleneck is the physical limits in transmission.

$$P_r = P_t*G_t*G_r*(\lambda/4\pi r)^2$$

  - At 1 GHz (λ=30cm) r=1m; Antenna gain @0dBm, free space loss factor is about **0.06%**
  - Even with a moderate gain transmitter antenna (6dBi) power received @1m for 1W transmission, is just 2mW.
    - Drops to 23μW at 10m !!
    - **The voltage of the signal is low!!**
- In radiative power transfer, Distance from transmitter is a major concern.

Some questions addressed in our work

- **Harvesting of ambient radiations or Radiative transfer of energy addressed**
  - Is it possible to harvest the RF energy from base stations
  - Are there other viable sources of RF energy

- Can low power communication systems be designed to operate entirely from harvested energy
  - Integrate sensors, control, etc

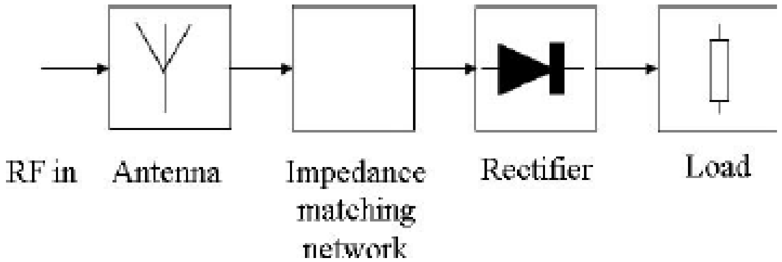
- Can we use RF EH/ WPT to increase the range of backscatter communication (RFID scenario)

Design of Rectifiers

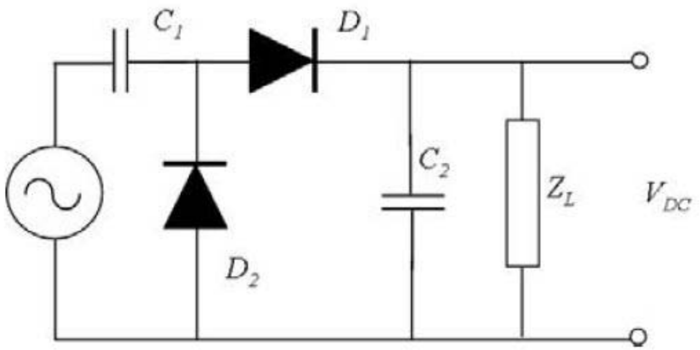
Required for converting incoming RF into DC power.

The challenge lies in maximizing the power conversion efficiency for low input power and minimizing the dimensions.

- RF to DC conversion by rectification of the incident RF signal by a ***Schottky diode***
  - Most diodes have a finite cut-in voltage
  - Diode is a non-linear device (performance depends on current or load)
  - Impedance matching required between antenna and diode
  - In most cases, the input voltage needs to be boosted



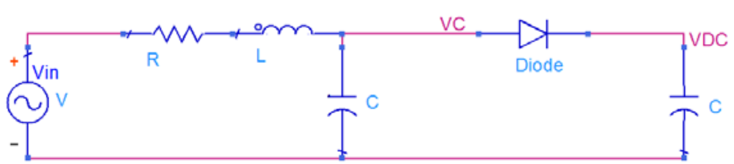
Conceptual diode based Rectenna



Voltage doubler

Voltage magnification in Matching circuit

- Matching circuit is required to provide impedance match between antennas (50Ω typical) to diode terminated with high impedance load (capacitor and/or high R in parallel).
  - LC matching networks provide voltage magnification.
  - This helps the diode conduct a good fraction of half cycle.
- The higher the voltage across the diodes, the more efficient the rectifier gets.
  - In practice Q is limited
  - Applications requiring higher voltages, a voltage multiplier configuration is used.



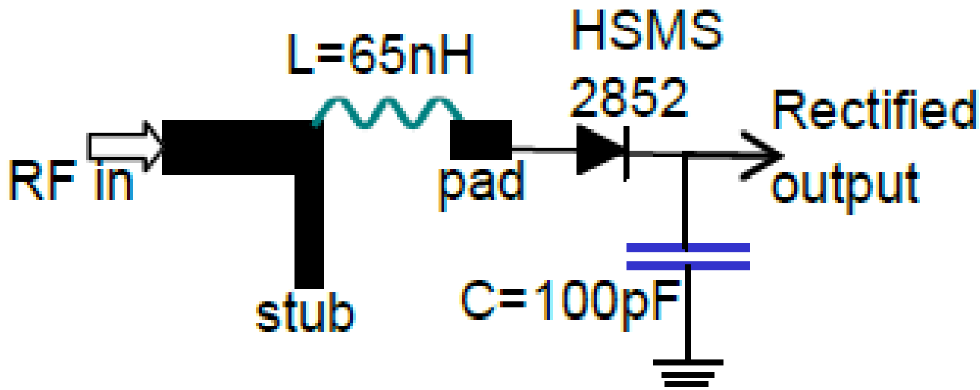
$$V_C = V_{in} \times \frac{\frac{1}{j\omega C}}{R + j\omega L + \frac{1}{j\omega C}}$$

At resonance,

$$V_C = V_{in} \times \frac{1}{j\omega_0 CR} = -jQV_{in}$$

Tuned Rectifier at RF

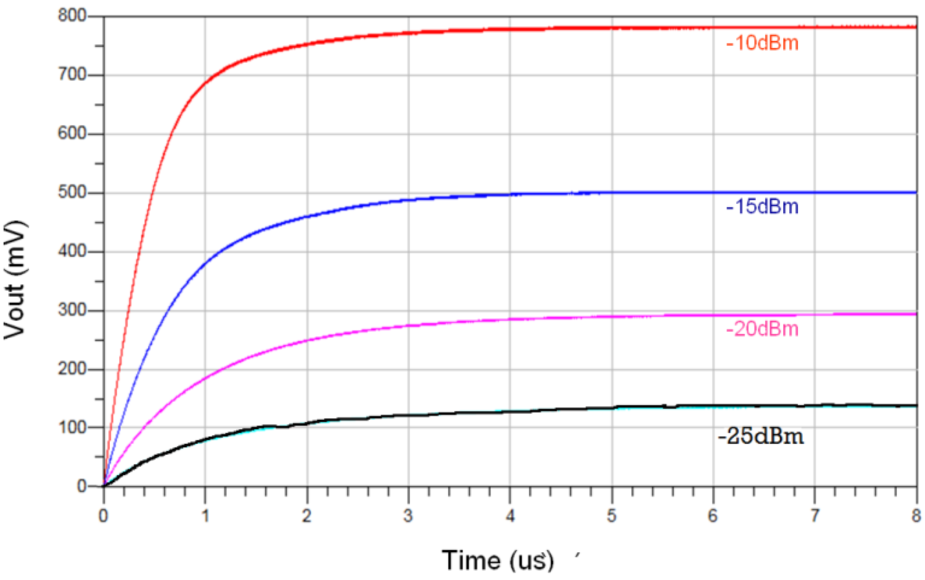
- A tuned rectifier implemented using discrete components

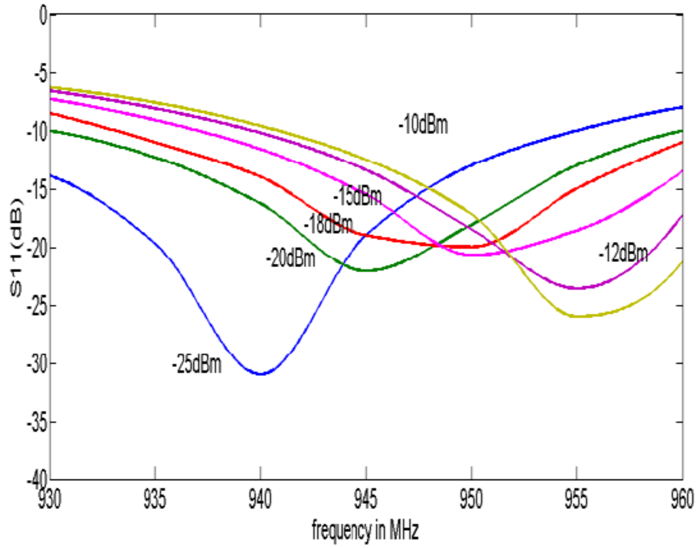


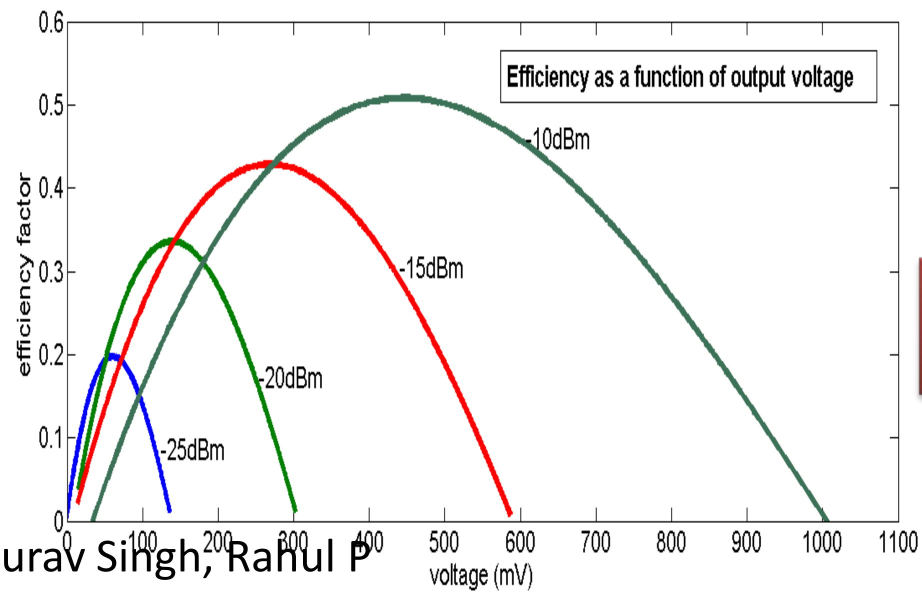
P_in→ Freq. ↓	-10dBm	-13dBm	-16dBm	-20dBm	-25dBm
930MHz	917mV	664mV	469mV	281mV	131mV
945MHz	1016mV	736mV	515mV	300mV	132mV
955MHz	1038mV	747mV	513mV	289mV	122mV
960MHz	1032mV	736mV	499mV	276mV	114mV
Peak efficiency	51%	47%	39%	33%	20%

K. J. Vinoy, T. V. Prabhakar, A Universal Energy Harvesting Scheme for Operating Low-Power Wireless Sensor Nodes Using Multiple Energy Resources, pp. 453-466, Micro and Smart Devices and Systems, Springer 2014.

Typical Performance of Rectifier

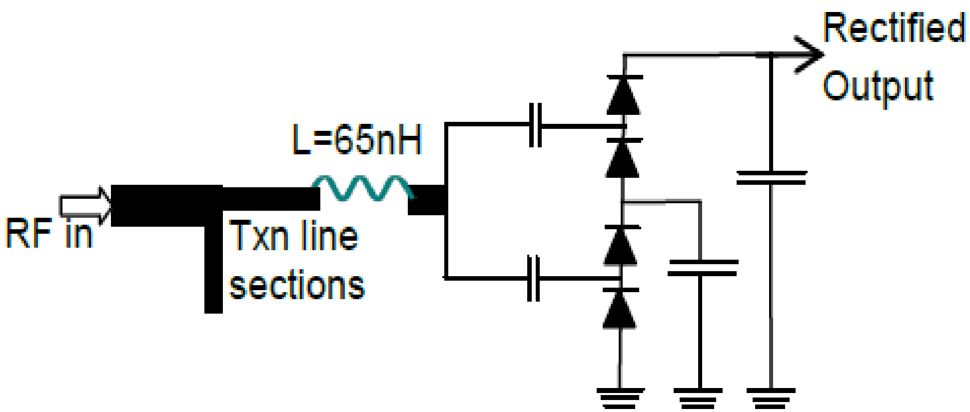






RF-DC Conversion efficiency depends on various conditions

Rectifier Circuit using 4 diodes

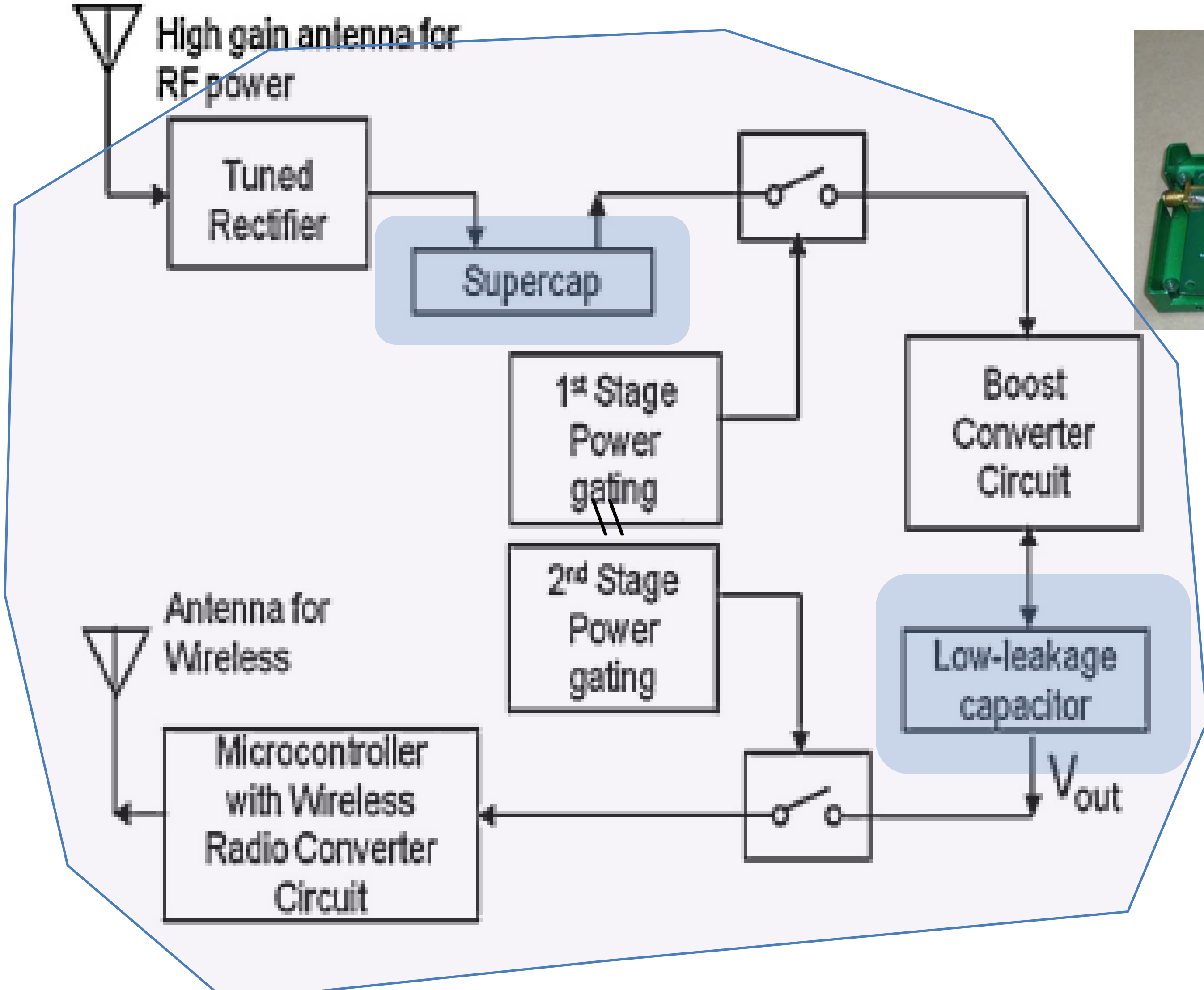


Power level (dBm)	Charging time (ms)	Efficiency (%)
0	40	64.11
-2	55	63.77
-3	67.5	63.5
-5	90	63
-7	230	59.89
-10	370	56.78
-12	500	53.89
-15	900	45
-18	2000	20.56

K. J. Vinoy, T. V. Prabhakar, A Universal Energy Harvesting Scheme for Operating Low-Power Wireless Sensor Nodes Using Multiple Energy Resources, pp. 453-466, Micro and Smart Devices and Systems, Springer 2014.

Aditya Mitra, Chaithanya (2011-12)

1: Scavenging Mobile Tower Radiations



G. Singh, R. Ponnaganti, T. V. Prabhakar, and **K.J. Vinoy**, “A tuned rectifier for RF energy harvesting from ambient radiations,” Int. J. Electronics & Communications, vol. 67, no. 7, pp. 564-569, July 2013

Gaurav Singh, Rahul P (2010-11)

Gaurav Singh, Rahul P (2010-11)

Characterization in Lab

- Using various antennas

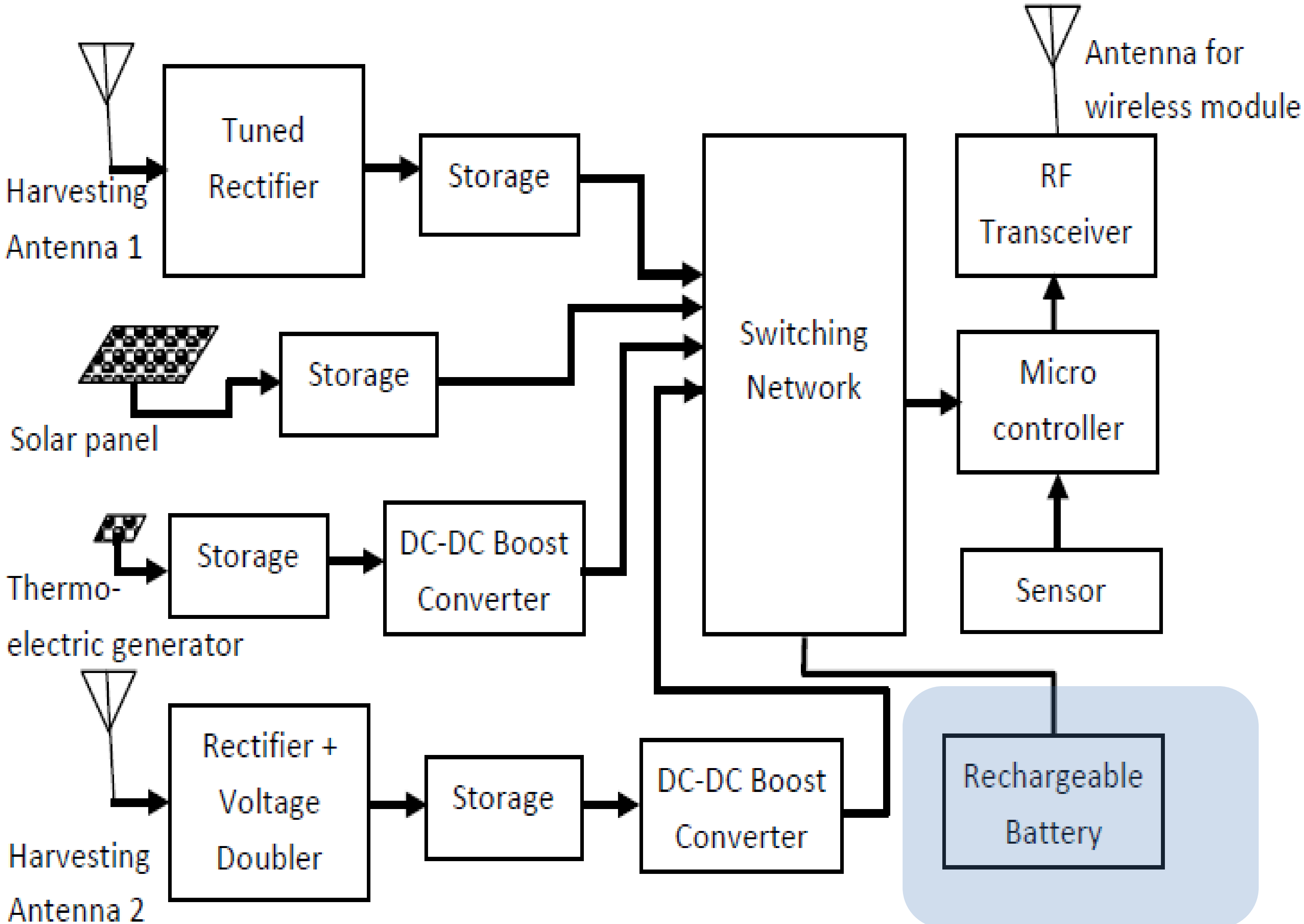
Distance from Transmitter [m]	1.5	2	2.5	3
Power received by dipole antenna [dBm]	-20.5	-22.1	-23.9	-25.2
Calculated power density [uW/cm^2]	0.078	0.055	0.035	0.03
Power received by patch antenna [dBm]	-15.1	-16.1	-17.6	-19.2
Transmit interval [mm:ss]	07:26	12:13	25:00	never
Power received by biquad antenna [dBm]	-11.8	-13.2	-14.9	-15.9
Transmit interval [mm:ss]	02:20	03:25	7:10	10:33

G. Singh, R. Ponnaganti, T. V. Prabhakar, and **K.J. Vinoy**, "A tuned rectifier for RF energy harvesting from ambient radiations," Int. J. Electronics & Communications, vol. 67, no. 7, pp. 564-569, July 2013

Gaurav Singh, Rahul P (2010-11)

Incident power above -18dBm required for operation

2. Universal Energy Harvesting Platform



Only a small thin film battery is used

UEHP: Performance with different sources

Solar		RF		TEG	
Light Intensity (Lux)	Duty Cycle of operation (s)	Power Level (dBm)	Duty Cycle of Operation (s)	Temperature Differential (^{o}C)	Duty Cycle of Operation (s)
1000	7	0	3	55	9
300	11	-5	6	45	13
200	**20**	**-7**	20	35	240
100	42	-10	50	-	-
-	-	-12	240	-	-

An incident RF power of -7dBm (~0.2mW) performs similarly as at low light PV.

An appropriately oriented 20mW source with a high gain antenna (~10dB) can reach this RF power at a low gain rectenna (eg using PIFA) at 1 m distance.
Power levels within emission guidelines…

K. J. Vinoy, T. V. Prabhakar, A Universal Energy Harvesting Scheme for Operating Low-Power Wireless Sensor Nodes Using Multiple Energy Resources, pp. 453-466, Micro and Smart Devices and Systems, Springer 2014.

Aditya Mitra, Chaithanya (2011-12)

Other Possibilities using Wireless Power Transfer

- Power transfer by radiation is not efficient
- Waveguiding systems can ensure better transmission of power
  - Loss in waveguide is a small fraction of a dB/m (~0.2dB/m)
  - Metal ducts may carry higher order modes with higher losses
  - Extended to conducting ducts, Tunnels, mine shafts etc with some compromise
- Other possibilities
  - Surface wave
  - Focusing of fields
- Empty enclosures with metallic walls
  - Containers, tanks, airplane cabin, trains, etc
  - Other objects in the path may reduce the efficiency!

3: Antenna for RFID sensors

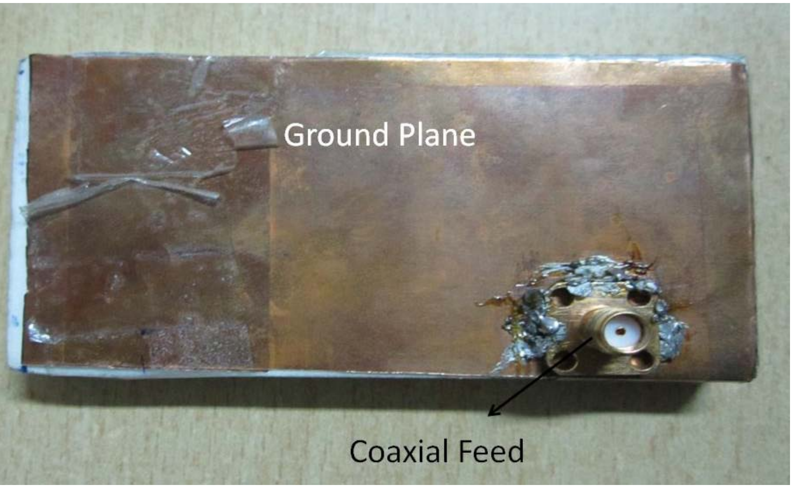
- Work involved design of antenna for RF harvesting sensors
  - These fuel level sensors to be deployed in a fuel tank of aircrft.
  - Optimization of design should focus on efficiency
  - High gain or directivity is not required.

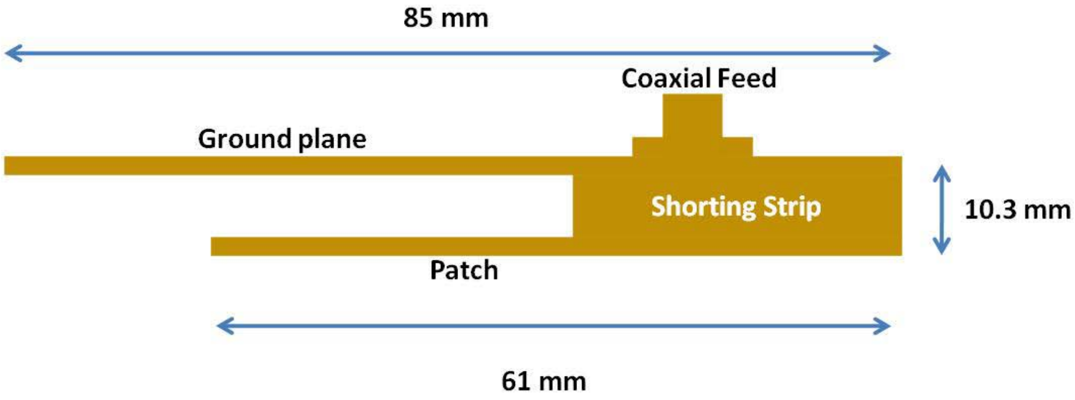
- EH platform to be used with RFID sensors deployed inside fuel tank

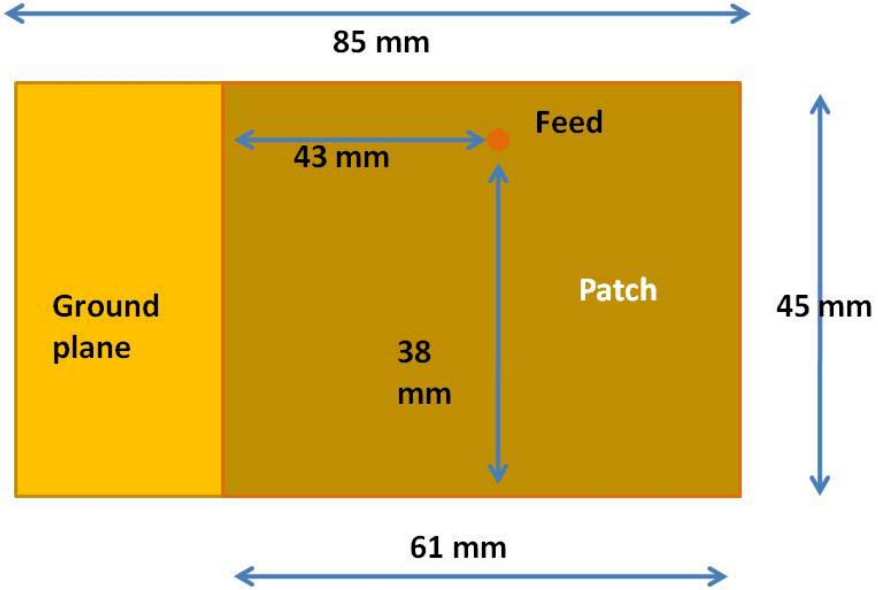
- Requirements/Assumptions:
  - Incident energy is of random polarity and direction.
  - Operating frequency is 902MHz-928MHz.
  - Antenna must operate in air (relative permittivity = 1) and fluid (relative permittivity = 2.1)
  - Dimensions of planar antenna board:
    - Target dimensions: 3 in. x 2 in.
    - Maximum dimensions: 6 in. x 4 in.

ANRC

Antenna Design dimensions

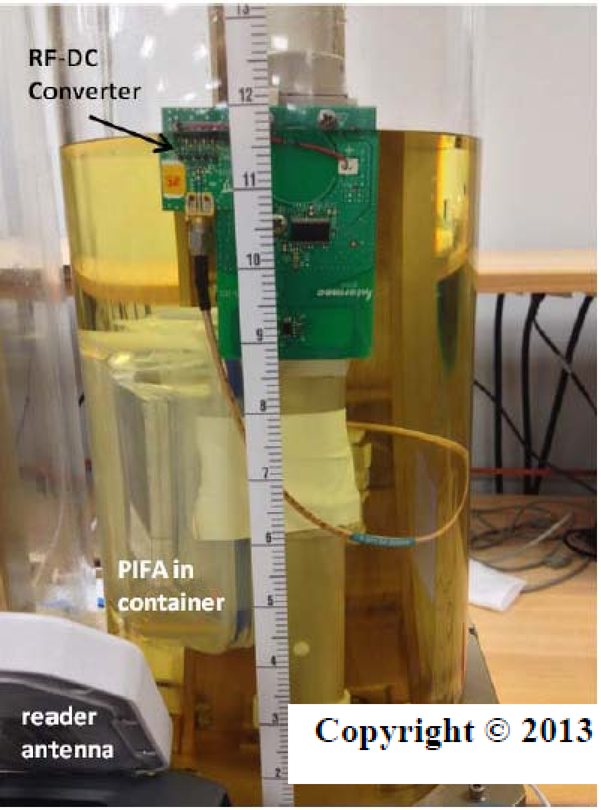


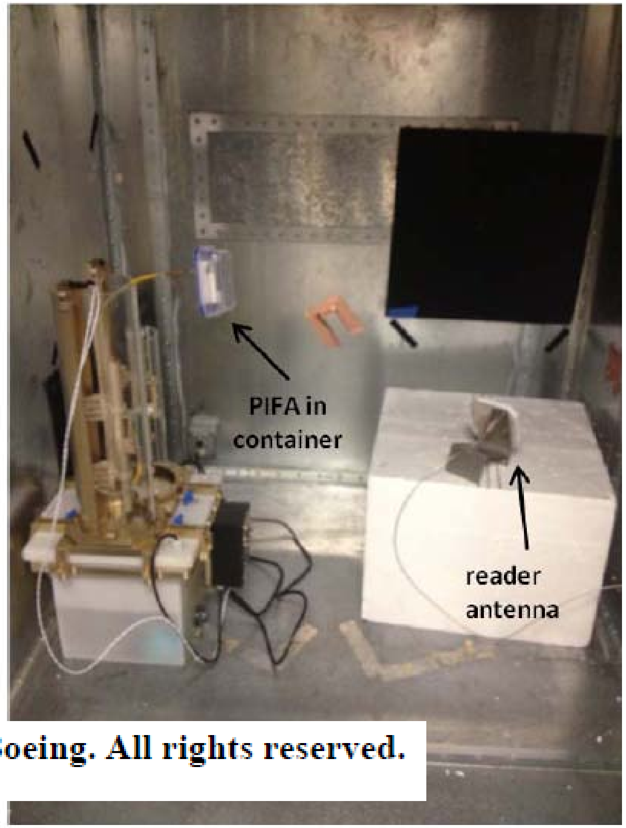




Vivekanand M, Harikiran M

Measurements at Boeing (Nov 2013)





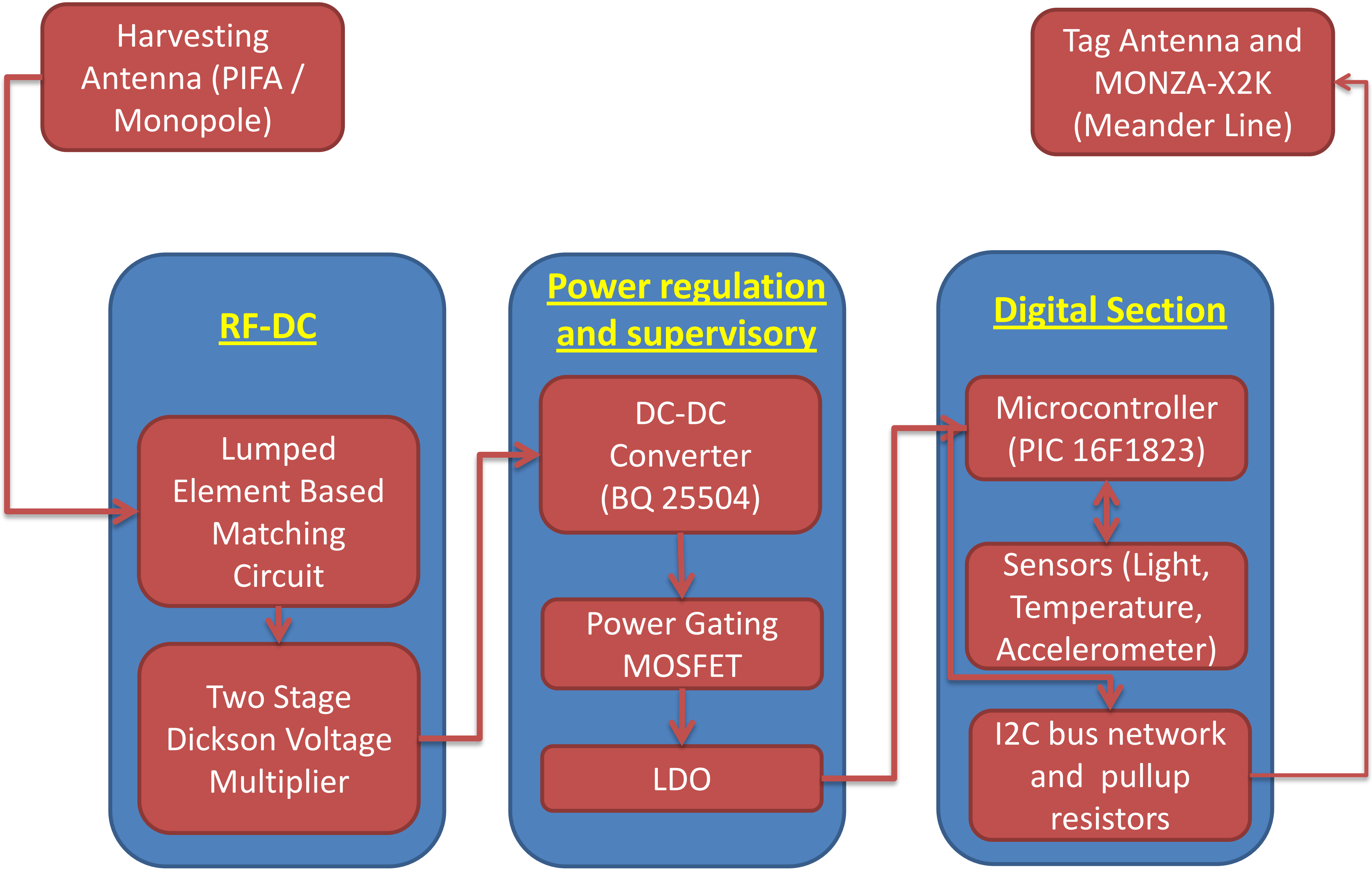
After Integrating with Sensor and RFID board;

Measured in a room and reverberation chamber

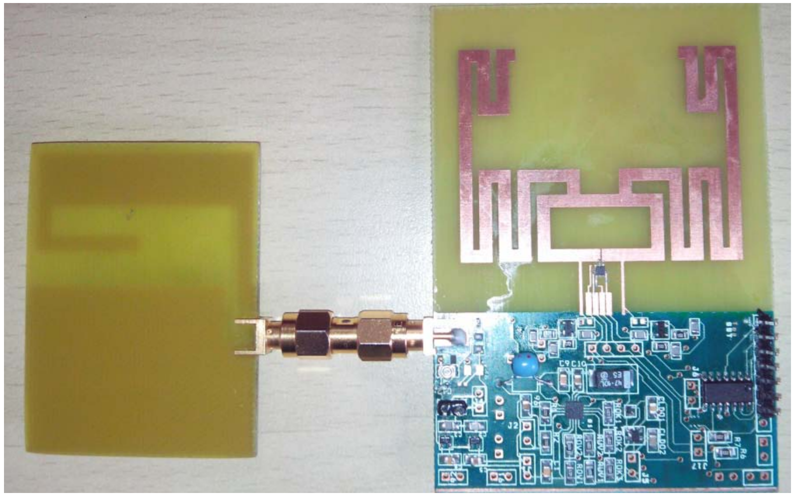
Resolution of fluid height measurement to within 0.25”.
1W maximum transmit power.
Uses a modified reader protocol.

A. Robb, J. Bommer, R. Martinez, J. Harrigan, S. Ramamurthy , H. Muniganti, V. Mannangi, and KJ Vinoy, “Wireless Aircraft Fuel Quantity Indication System,” 2014 IEEE Sensors Applications Symposium - , Feb 18-20, 2014, Queenstown, Newzealand.

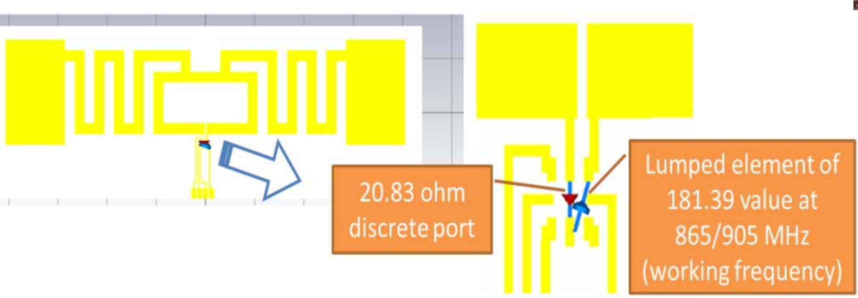
4. RFID Integrated with Sensor

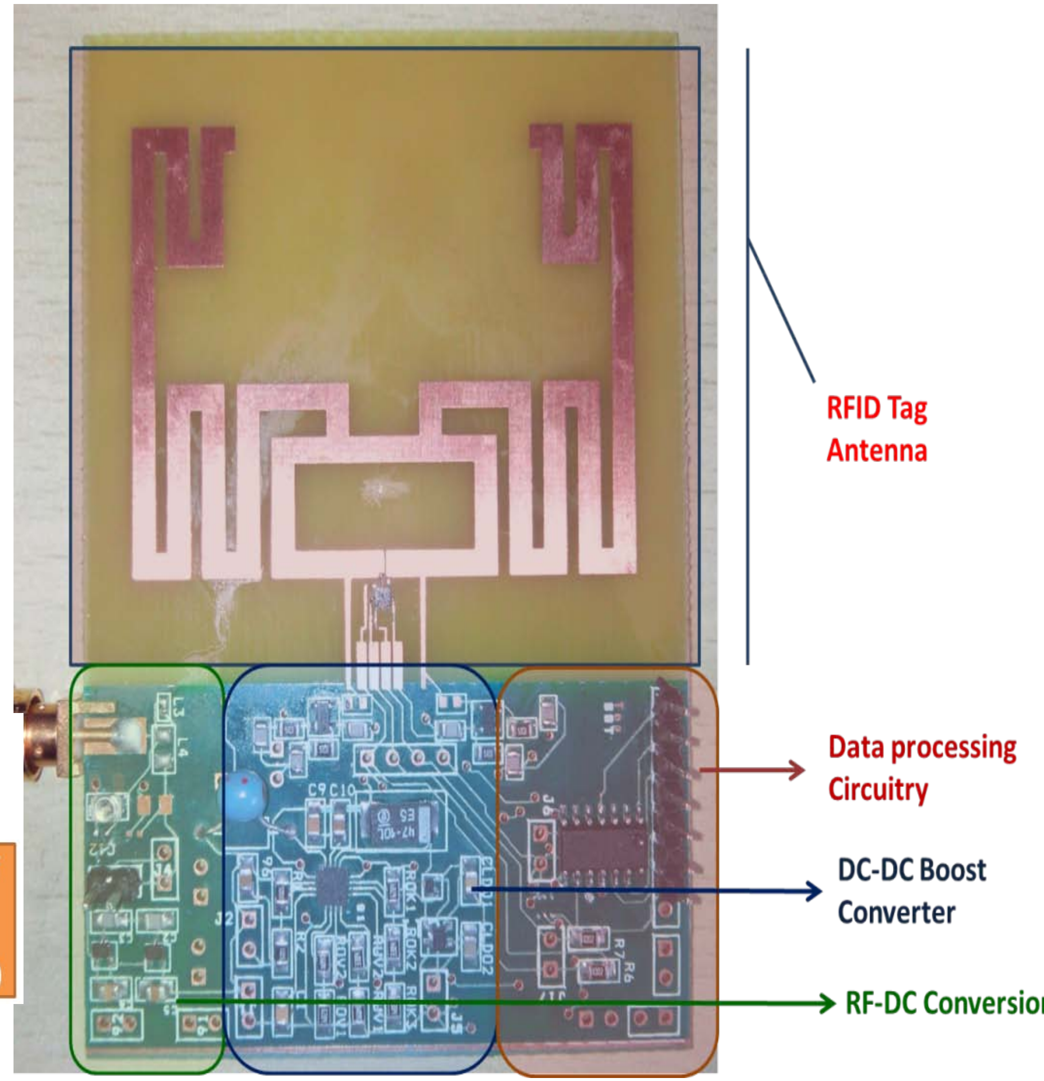


Parts of Fabricated System



PIFA CONNECTED SENSING TAG





Sandeep Rana 2014-15

Sandeep Rana, TV Prabhakar, KJ Vinoy, An Efficient Architecture for Battery-less Terminals for Internet of Things, Applied Computational Electromagnetic Conference, Guwahati, Dec 28-21, 2015

Characterization of Performance

Source	Power
RFID Reader	30 dbm
Circularly polarized antenna	8 dbi
Polarization loss	3 dbi
Monopole Antenna	5 dbi
PIFA antenna	1 dbi
Meander Antenna	0.4 dbi

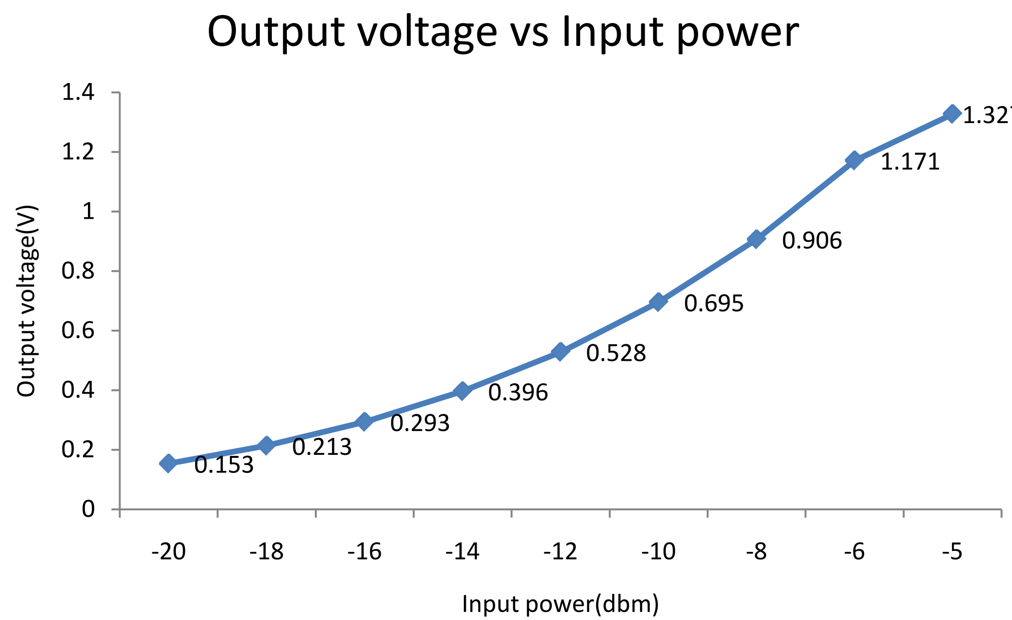
Tag Antenna	EIRP (dbm) + Gr	Rg Expected (-10 dbm) and 50 % overall efficiency	Range Achieved
Monopole	40	7.5 mtr	7 mtr
PIFA	36	5 mtr	5.5 mtr
Meander Line	35.4	4.5 mtr	4.5 mtr

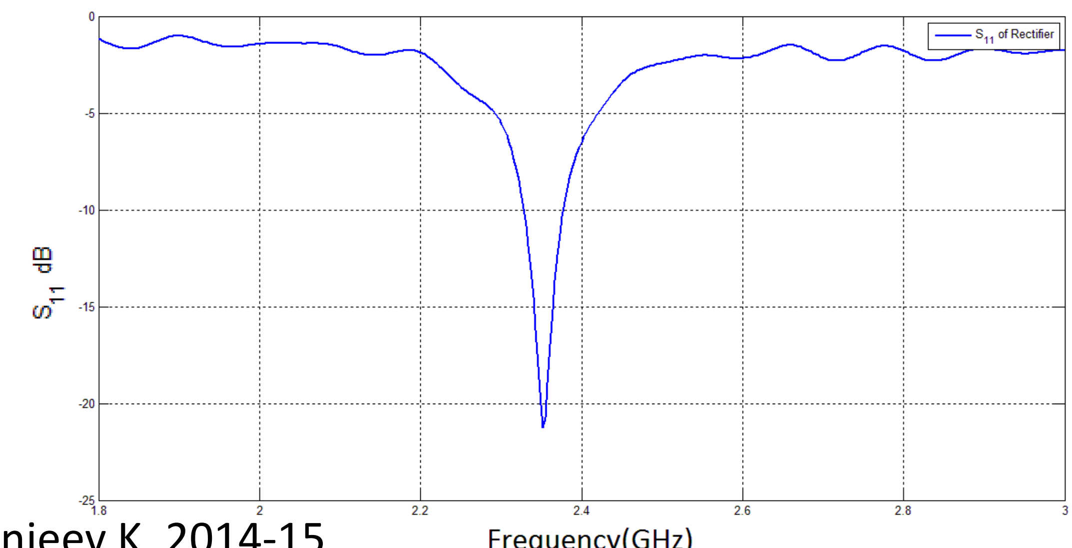
$\lambda = 34.5\ cm$ $\quad$ $\text{Prx} = \text{EIRP} * \text{Gr} * \left(\frac{\lambda}{4*\pi*r}\right)^2$

Efficiency worked out for -10 dbm
RF-DC efficiency – 20 % and DC-DC efficiency – 80%
Overall efficiency – 16%

Sandeep Rana 2014-15

5. Harvesting at 2.4GHz





Comparison of Efficiencies

Schottky diode

	900MHz	2400MHz
-15dbm	Efficiency=47% Output voltage=0.29V Load resistor=6K	Efficiency =17% Output voltage=0.2V Load resistor=6K
-20dbm	Efficiency=31% Output voltage=0.15V Load resistor=6K	Efficiency=5% Output voltage=0.1V (0.153V unloaded) Load resistor=6K
	Used HSMS 2852	Used HSMS 2862

Diode connected MOS with high Q matching

	900MHz	2400MHz
-14dbm	Efficiency=6.2% Output voltage=1.1V Load resistor=500K	Efficiency=2% Output voltage=0.632V Load resistor=500K
-20dbm	Efficiency=1.8% Output voltage=0.3V Load resistor=500K	Efficiency=0.2% Output voltage=0.118V Load resistor=500K

Zero V_{TH} CMOS

	900MHz	2400MHz
-15dbm	Efficiency=4.6% Output voltage=0.86V Load resistor=500K	Efficiency=3.79% Output voltage=0.774V Load resistor=500K
-25dbm	Efficiency=2.4% Output voltage=0.198V Load resistor=500K	Efficiency=1.7% Output voltage=0.165V Load resistor=500K

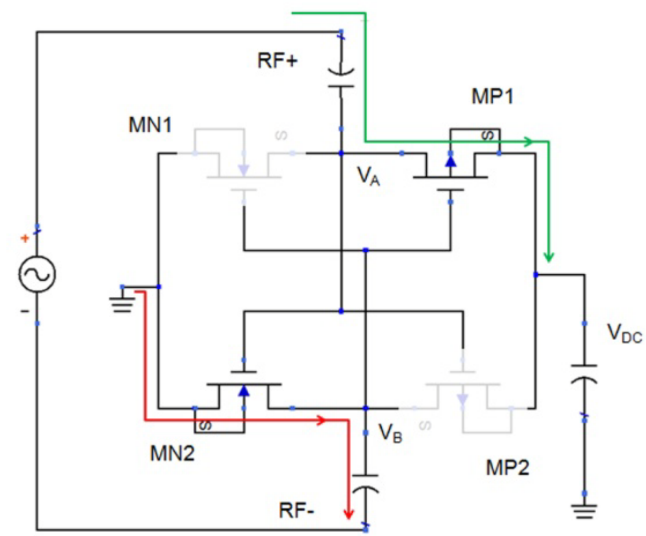
Power ↓

Technologies ↓

Frequencies →

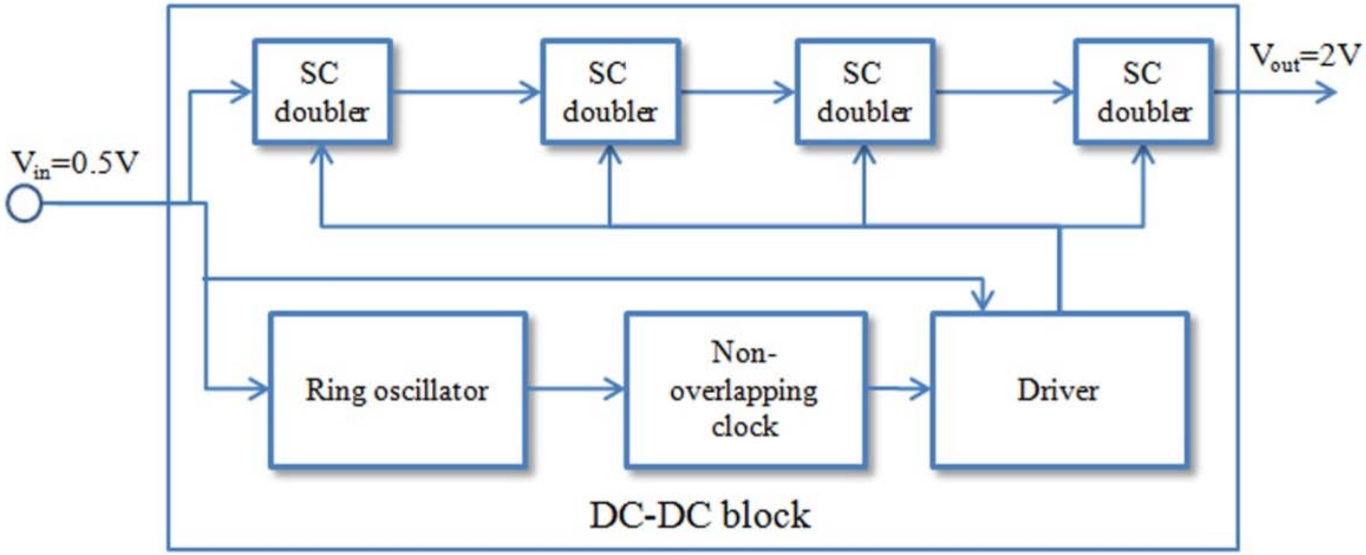
Cross-coupled Rectifiers for Low Power

- CMoS integration requires diodes using MoSFETs.
- Simple diode connected configurations are not effective at low power/voltage levels
- In Cross Coupled Rectifiers
  - Biasing of MOSFETs by charge stored in capacitors. This is a way of threshold compensation.
  - Low ON resistance due to high overdrive voltage.
  - In both cycles of input, output capacitor is charged. Although DCP uses both cycles, only alternate cycles charges the output capacitor and the other cycle charges the input capacitor.

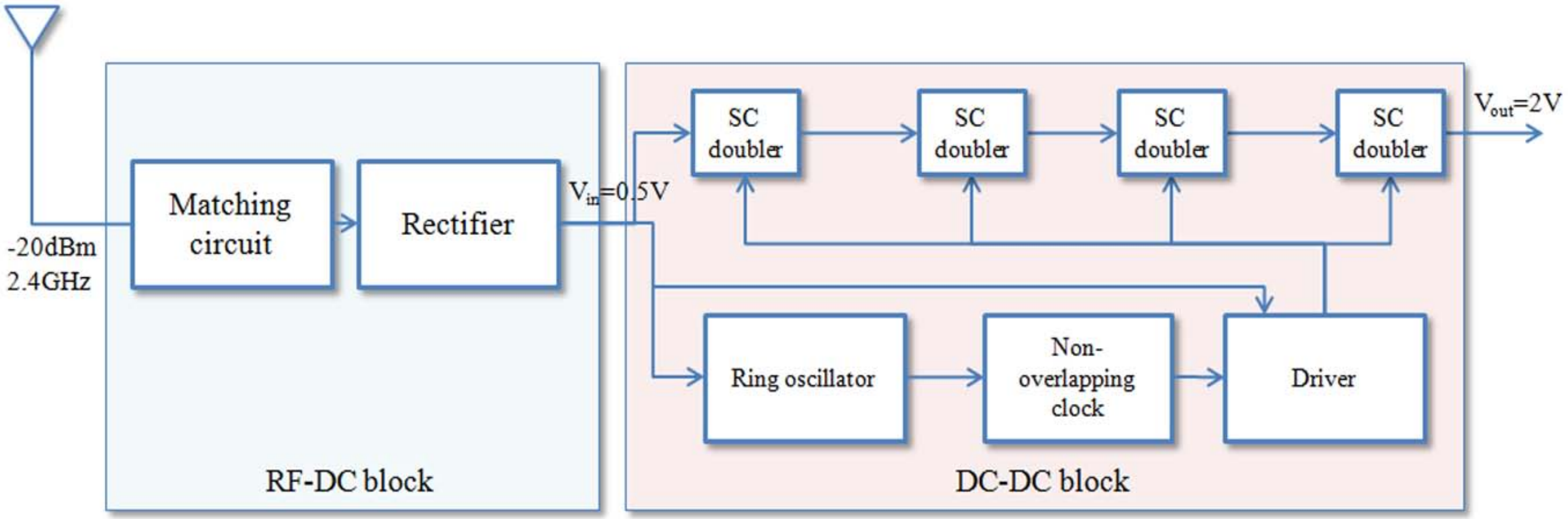


DC-DC converter

- Low loss switched capacitor DC-DC converter:



Full system block diagram



1. Output capacitor of RF-DC supplies DC-DC
2. Enable generator logic constructed using back to back inverters
3. 5 MOSFETs added to limit supply voltage to ring oscillator

RICOH
imagine. change.

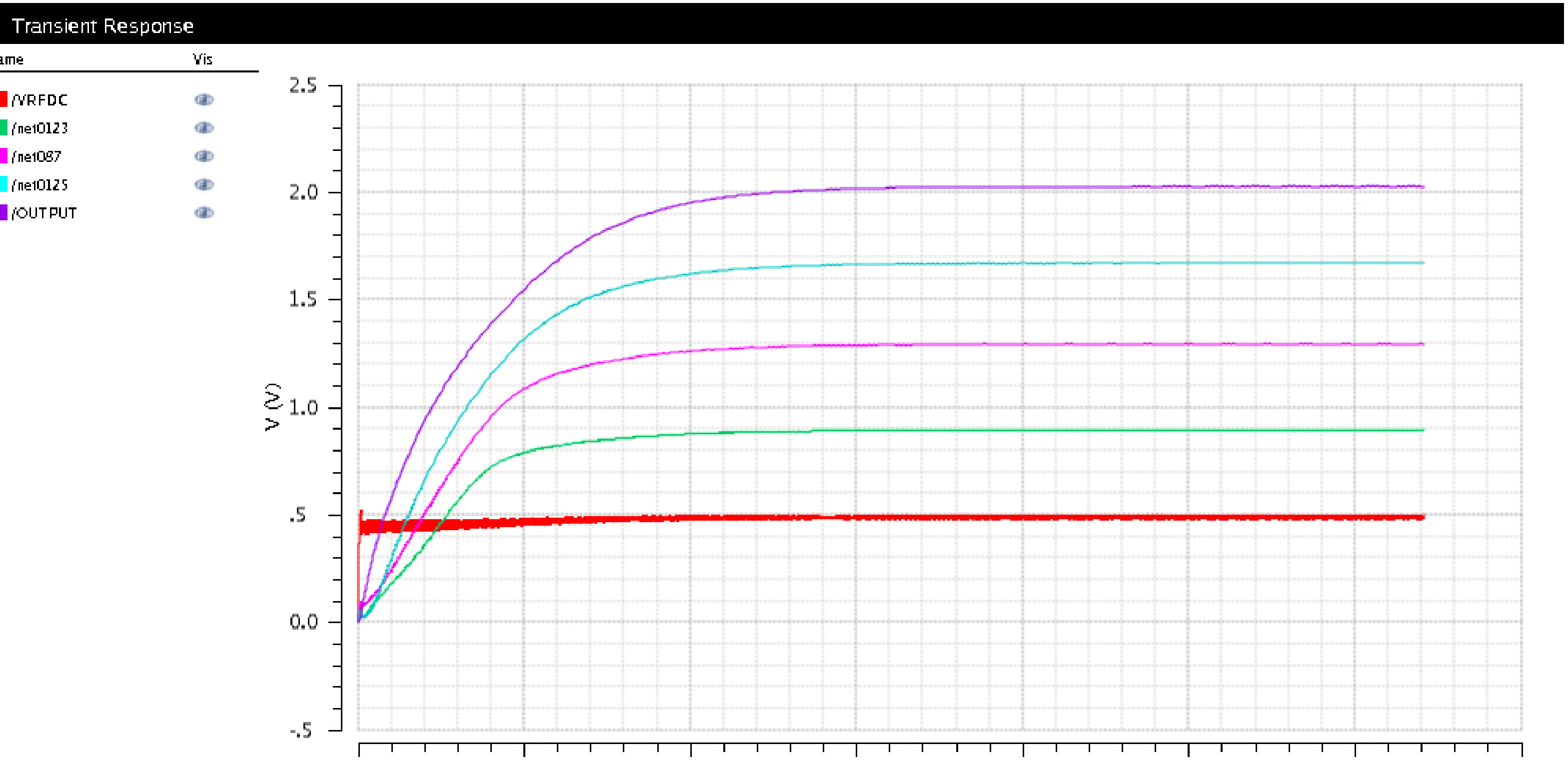
Sanjeev K, Manjunath M, TV Prabhakar, KJ Vinoy, Some Practical Considerations of RF to DC Converter using Low Vth CMOS Rectifier, Applied Computational Electromagnetic Conference, Guwahati, Dec 28-21, 2015

Full system simulations

- Output capacitor of RF-DC loaded heavily when clocks transition, so ripples exist in RF-DC output.
- Below 0.5V at clock transitions, above 0.5V between clock transitions
- Time step is 8ps for RF-DC simulation and DC-DC has to run for hundreds of µs or few ms, so simulations times are large.

Output voltage=2V across a load of 1.6MΩ, which gives

$$Efficiency = \frac{2^2/1.6\times10^6}{10^{-5}} = 25\%$$



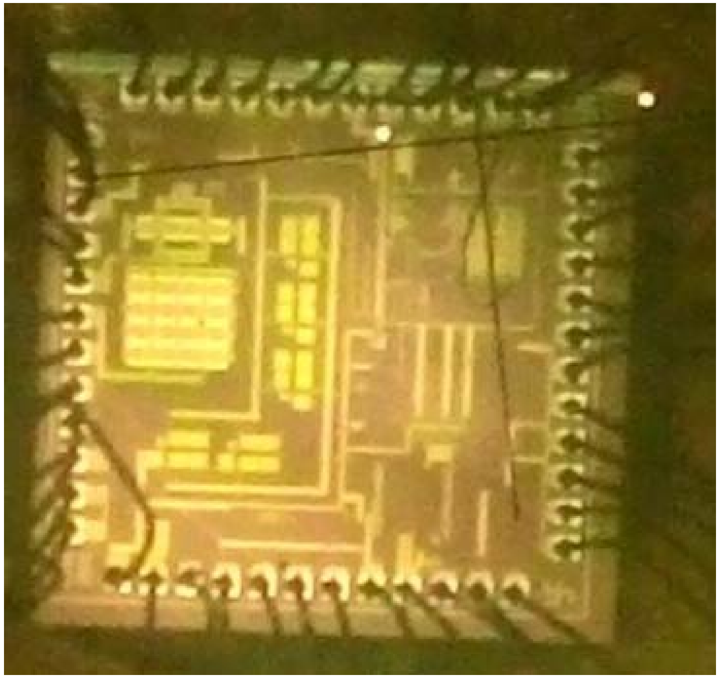
Summary with IC Design

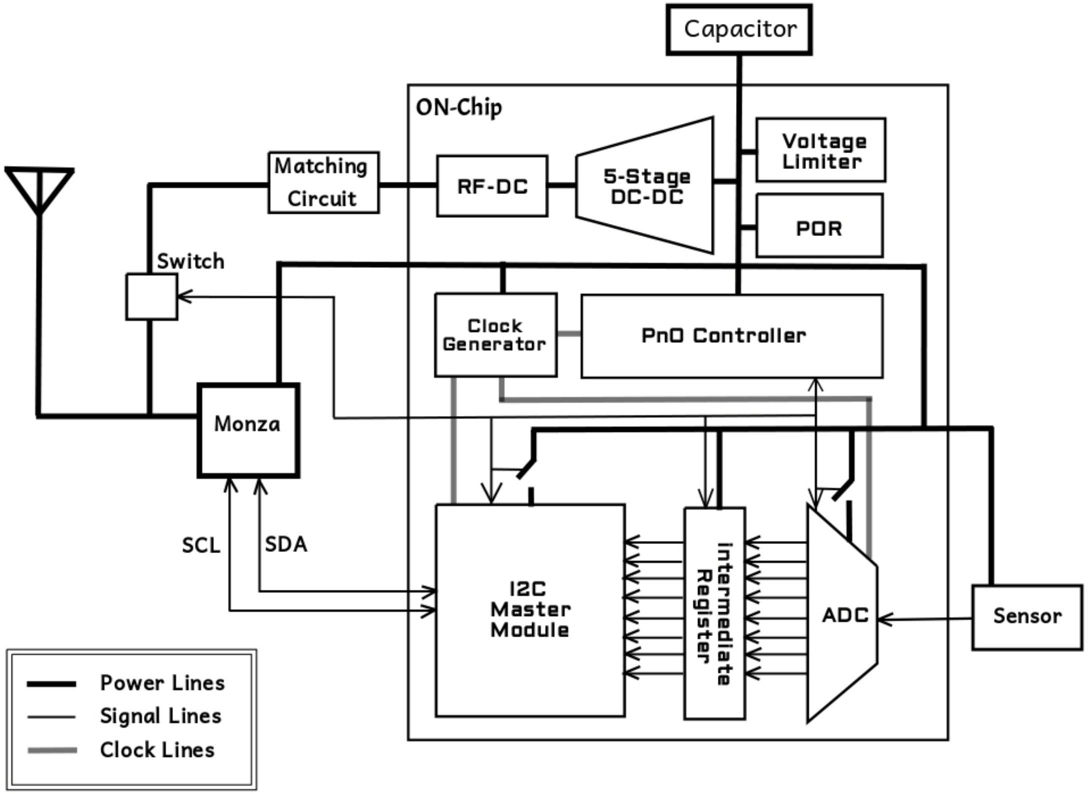
- Low Vth NMOS based DCP gives 42.3% efficiency.
- FGCCR gives 55% efficiency.
- The overall system efficiency is 25%.
- Higher than efficiency reported in literature for RF-DC converter operating at -20dBm, 2.4GHz in 130nm technology.

Reference	This work	[5]	[7]	[6]
Power level	-20dBm	-25.7dBm	-22.6dB	-20dBm
Frequency	2.4GHz	2.45GHz	906MHz	2.4GHz
Efficiency	55%(simulated)	37%(measured)	10%(measured)	36%(simulated)
Rectifier	FGCCR in UMC 130nm CMOS	DCP in 0.5µm Silicon on Sapphire	DCP with floating gate transistors in 0.25µm CMOS	FGCCR in 130nm CMOS

6. ASIC Design for IOT

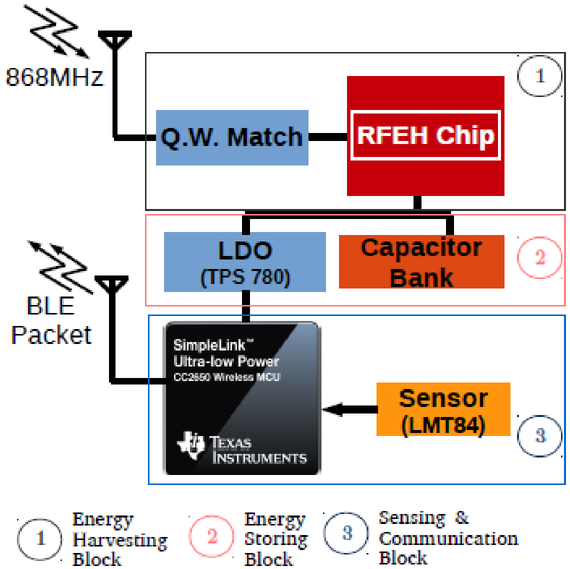
- Working on a 3-chip architecture
  - Our chip to enable sensing, and control functions
  - Communication using an external Monza chip
- Fabricated chip using commercial services!!

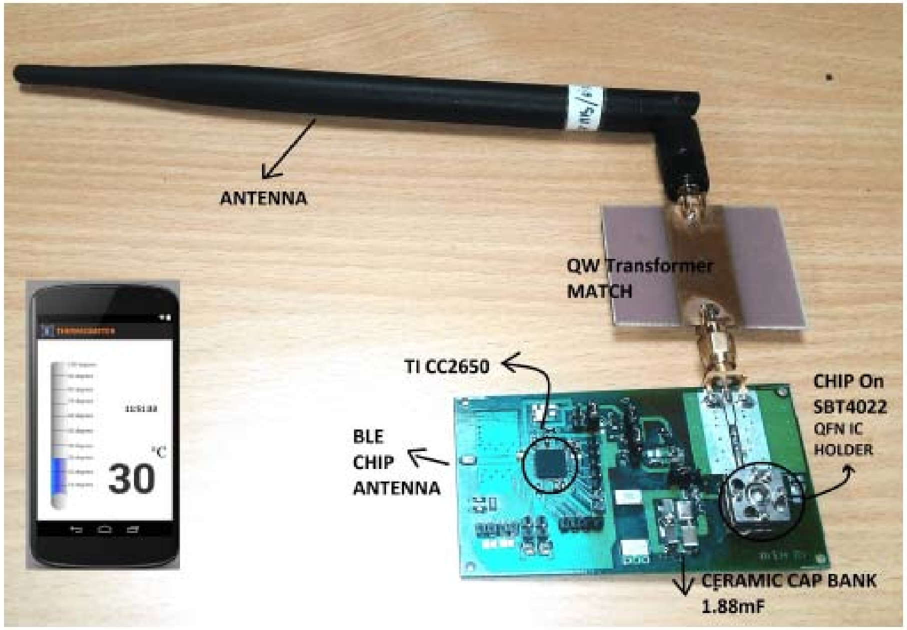




Bharat Hegde & Syed Younis 2015-16

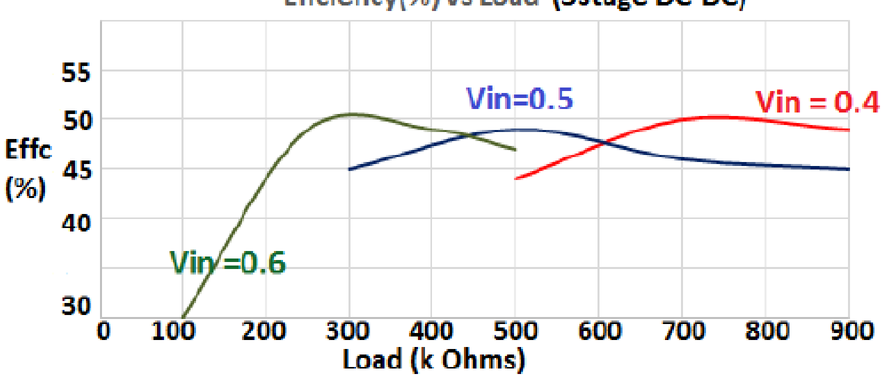
Battery-less Sensor node for BLE

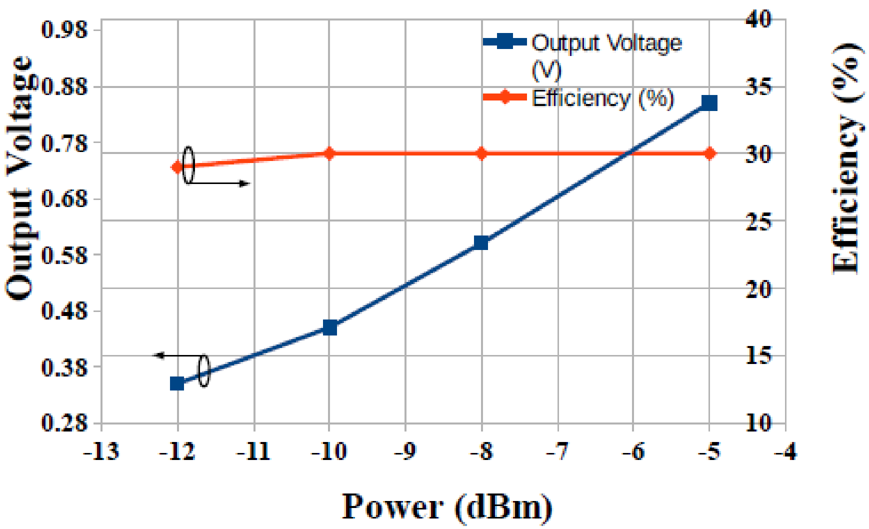




Distance from Reader (m)	Input Power (dBm)	Cold Start Time (min)	Packet Time (min)	Efficiency (%)
3	-2	15	1.75	2.2
4	-5	35	7	1.7
5	-8	120	32	1

Eficiency(%) vs Load (5stage DC-DC)





Bharat Hegde & Syed Younis 2015-16

Summary

- Most low power wireless terminals operate intermittently
- These require anywhere 50uW to about 10mW for their operation.
  - Batteries limited: cost, size, stored energy
  - Solar: not dependable through
- WPT and RF EH can enable wide use of IoT
  - Main challenges in the design is the low incident energy/power/voltage
  - High Quality factor components may help
- Several fabricated examples discussed here: All can transmit data to an aggregator wirelessly
  - Different standards implemented.

Acknowledgements

- Dr. TV Prabhakar, DESE, IISc
  - Gaurav Singh
  - Rahul P
  - Chaithanya C
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  - Prashanth Raja
  - Nirmal John
  - Nithin Jose
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  - Niharika Thakuria
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- Prof Bharadwaj Amrutur
  - Uday S
  - NS Sreeram
- Others
  - Vivekanand M
  - Harikiran M
  - Manjunath M
  - Sanjeev K
  - Sandeep Rana

Thank YOU